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THE GENERAL PRINCIPLES UNDERLYING METAMORPHIC PROCESSES

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PART I

INTRODUCTION

The term metamorphism in its widest sense includes all the alterations which occur in solid rock; it therefore comprises those processes which change the composition (mineral or chemical), structure, and texture of rocks after they have been formed, no matter what may have been their origin—by solidification from magma, consolidation of chemical precipitates, or mechanical deposit. But we, following Grubenmann, shall limit this somewhat and consider as typical cases of metamorphism only those in which the effects produced by the alterations determine completely the character of the rock mass.

An essential characteristic of metamorphic alterations is that the rock *as a whole* remain solid during the process. This condition does not hold whenever the original rock has at any instant been wholly melted; such a case is merely a solidification under special conditions from a magma, and the rock formed in this way is indistinguishable from an eruptive rock. When once a rock has been completely melted, we can say nothing of its particular history previous to that time; in especial we cannot know whether any of the components of the rock have existed previously as solids.

The crystalloblastic structure[1] described by F. Becke and by U. Grubenmann could not be accounted for if the new-formed rock had been formed out of a completely fluid medium, but is easily correlated with all the other properties of rocks formed by metamorphism if we regard the change to be the result of a process of melting (or of solution) which at any instant is local and partial only.

Metamorphism of rocks is effected by change of temperature, of uniform pressure, of stress, and of concentration; it occurs whenever the original components become unstable by reason of the changed external conditions, provided always that the velocity of reaction is appreciable. The above are the important factors in determining any chemical equilibrium, so that in the study of metamorphic processes it is necessary only to apply well-known physico-chemical principles to these special, and in general complicated, systems; indeed a beginning in this direction has already been made, in the well-known work of Van Hise, Becke, Grubenmann, and V. M. Goldschmidt.

The opinion has been held that physico-chemical principles are incompetent to account completely for the phenomena of metamorphism, for the reason that the system is in many cases not in a state of true equilibrium, either during the process of metamorphism or after alterations of the system have practically ceased. This lack of stable equilibrium is due to the small rate of reaction under the particular conditions, and hence is part of the large physico-chemical problem of the relation between rate of reaction and the general properties of the system or of its components.

To grasp the general effects produced by the various agents concerned in metamorphic processes is easy, even though quantitative data are still lacking; but the application of these principles to particular cases demands a clear and well-defined knowledge of

[1] It is to be remarked that the words *Textur* and *Struktur* have a signification in German which is different from the meaning usually attached to their equivalents in English. According to contemporary German usage, which is based on the definitions given by Becke and Grubenmann, *Textur* is arrangement in space, while *Struktur* is used to express genetic relationship. Hence crystalloblastic structure has nothing to do with textural relationships such as are observed in flow cleavage; for instance, the structure of the massive eclogites is typically crystalloblastic.

their effectiveness and limitations, in order that effects may not be attributed to causes which are incompetent to account for them. The present paper is an endeavor to discuss the validity, the limitations, and the relative importance of the general principles involved; our aim has been, in bringing them definitely to the attention of geologists, to show that it is no simple matter to apply these principles, simple in themselves, to the very complicated systems encountered under geological conditions, and that very careful reasoning is required if correct conclusions are to be reached. We wish to emphasize especially the distinction which must be made between uniform pressure and non-uniform compression or stress. The importance of uniform pressure, and the magnitude of the effects producible by it, have frequently been overestimated, while on the other hand insufficient account has been taken of the comparatively much greater effects which may result from the action of non-uniform compression.

We shall not go into the various kinds of metamorphism—regional-, contact-, dynamo-metamorphism, etc., for in all cases the final effect is determined by the same factors, namely, temperature, pressure, stress, chemical composition,[1] and speed of reaction. One factor may be predominant in one kind of metamorphic process, another factor in a second; but by combination of the above factors, all of the observed effects attributed to metamorphism may be accounted for.

In the following pages we present a discussion of the most important general principles involved, especially of those principles which have not always been applied correctly by those who have made use of them. We have, for the sake of clearness, divided up the subject-matter under a number of headings, to which we have, however, deemed it inadvisable to adhere strictly throughout; these are intended to be read only in the light of the general context, as it was impracticable to insert always the qualifying phrases required to render the statements strictly accurate. Moreover, this paper does not pretend to completeness, either from the chemical or from the petrologic side; it aims to treat the various

[1] By this is to be understood the gross chemical composition of the whole system at the period of metamorphism, and not the chemical composition of the rock-mass now.

topics only in so far as they are important in regard to metamorphic processes.[1]

Furthermore, the references to previous work are in no wise to be understood as a bibliography of the subject; they are given merely as illustrations, or expansions, of the ideas in the text, and have been chosen from the work with which the writers happen to be most familiar.

In pursuance of this plan, we give first a brief discussion of the general effects of temperature and pressure, followed by sections dealing with the general behavior of systems when exposed to (1) uniform pressure, (2) non-uniform compression or stress. Chemical composition is always specific and characteristic of the particular system; therefore it cannot be discussed in a general way, but must be ascertained by experiment for each system. A similar remark applies to rate of reaction.

EFFECTS OF TEMPERATURE AND PRESSURE ON SYSTEMS SOLID-SOLID[2]

General considerations.—A very large number of all crystalline substances exist in more than one crystalline form;[3] thus silica appears in at least seven distinct forms, sulphur in at least four solid forms, and so on. And it is a matter of common knowledge that further and more extended investigation always swells the list of polymorphic substances; so that it would appear as if poly-

[1] For fuller information on the chemical topics the reader is referred to textbooks of theoretical chemistry: the more elementary books of Walker, *Introduction to Physical Chemistry* (Macmillan), or Senter, *Outlines of Physical Chemistry*, the larger general works of Ostwald, *Allgemeine Chemie*, or Nernst, *Theoretische Chemie*, or the more special books, such as Roozeboom's *Heterogene Gleichgewichte* or those in the series edited by Ramsay and published by Longmans; on the petrologic side, to books such as Harker, *Natural History of Igneous Rocks*, Elsden, *Principles of Chemical Geology*, and especially to Grubenmann, *Die kristallinen Schiefer*. Doelter's new *Handbuch der Mineralchemie* is a collection of observations, rather than a critical discussion of the subject, and it is not entirely free from errors of interpretation.

[2] Throughout this paper the term solid is used to designate *crystalline* material, as distinct from amorphous material (glasses); the latter are merely subcooled liquids, which differ from ordinary liquids only in that their viscosity is almost immeasurably greater.

[3] A fairly complete list of the instances known up to 1893 will be found in Arzruni, *Physikalische Chemie der Krystalle* (Braunschweig, 1893).

morphism were the rule rather than the exception, at least with inorganic substances, especially with those of geologic interest. Let us consider what happens when we heat very slowly a substance capable of existing in more than one polymorphic form; and for the sake of simplicity, let us assume that the substance exists only in two forms, which we may designate as α and β. This assumption of only two forms really implies no limitation of generality, for even with a substance which may be obtained in more than two forms we are dealing with only two of them in the neighborhood of any single transformation temperature. Now as we slowly heat the α form, we find a slow but continuous change in its physical properties:[1] e.g., in density, refringence, and (in general) axial ratios; this gradual change goes on, until finally we observe a much more marked change of properties—which may take place either at a definite temperature or within a small range[2] of temperature—denoting that the transformation into the β form has been effected. Further heating now is accompanied anew by a gradual change of properties, a change characteristic of the β form and bearing no necessary relation to the corresponding changes shown by the α form.

If now we cool again through the transformation temperature, the α form may or may not appear. Failure to reappear may be due to one of two causes: (1) that *under the particular conditions* the rate of transformation of β into α is extremely slow, or, in other words, the attainment of equilibrium requires a long time; (2) that the equilibrium between β and α is such that β is the stable form throughout the temperature range in question; consequently α can then not appear no matter how much time is allowed.

Transformations belonging to the first class—that is, where equilibrium can be attained from either side—are known as *enantiotropic;* changes which are irreversible are called *monotropic.* We shall discuss these separately; but before doing so, we wish to direct attention to a point which, though important, is often lost sight of.

[1] A much more profound, though continuous, change is of course possible, e.g., on heating zeolites and other hydrous minerals (see F. Rinne, *Fortschritte Min.*, 1913 (3), 159–83).

[2] At least, if the rate of heating has been small.

Importance of the rate of transformation.—The point in question is that the factor which determines the actual experimental result may be the rate at which equilibrium is established under the particular conditions. We must therefore always ascertain whether the observed result is, or is not, due to a laziness—as opposed to an inability—to react; in other words, we must distinguish carefully between cases of true and *apparent*, or false, equilibrium. Lack of care in this matter may lead us to consider a transformation to be monotropic or a given form to be stable under conditions where it really is metastable, its persistence in either case being merely the result of a slow rate of transformation.

As an illustration, take the system represented by the scheme $2H_2+O_2 \rightleftarrows 2H_2O$, a system which has been so thoroughly investigated[1] that we know the conditions of equilibrium at all temperatures up to 2,600°. These conditions are such that at all temperatures below 1,000°, the pressures of oxygen and hydrogen which can exist in real equilibrium with water are infinitesimally small;[2] hence, if *real* equilibrium obtained, it would be altogether impossible to preserve in presence of water an appreciable amount of a mixture of oxygen and hydrogen. In other words, this system is, theoretically, absolutely unstable; *practically*, however, hydrogen and oxygen may be left in contact together with water for an unlimited time at ordinary temperatures, and still show no signs of reaction, which begins only at fairly high temperatures, i.e., when its velocity becomes appreciable.

This case is instructive also in showing that there is no necessary parallelism whatever between the "affinity" of two substances for one another (which is measured by the change of free energy accompanying a reaction) and the rate of reaction under any particular conditions. Thus the above reaction does not go (except at high temperatures), although the energy change accompanying it is one of the largest known; on the other hand, many reactions with comparatively feeble energy changes go quite readily. Moreover,

[1] See Nernst, *Theoretische Chemie;* Bjerrum, *Z. physik. Chem.*, LXXIX (1912).

[2] Thus the extent of dissociation is of the order of 10^{-25} per cent at 25°, 10^{-5} per cent at 700°, and does not reach a magnitude which is directly measurable until about 1,200°, where it is about 0.02 per cent.

if there were a definite connection between heat of reaction and rate of reaction, the existence of endothermic compounds would appear to be highly improbable, if not impossible.[1]

The rate of reaction varies enormously with the temperature, in general doubling for a rise of 10°. A rise of 100° therefore causes a reaction to go about one thousand times faster, while its speed is increased about a million times when the temperature is raised about 200°. In accordance with this we find that the rate of transformation of one crystal form into another tends to be greater the higher the temperature at which the transformation takes place.[2] There is very little direct evidence with regard to the effect of pressure on the rate of reaction (as distinguished from its effect on the position of equilibrium); such as there is indicates that it has little, if any, effect.[3] In any case it is a safe assertion that the effect of pressure on the rate is absolutely negligible as compared with the enormous acceleration produced by change of temperature.

The rate of a reaction is quite generally much affected by the presence of certain specific substances; thus, palladium black brings about the union of oxygen with hydrogen around 100°. Such substances affect only the rate at which equilibrium is established, but are usually understood to be without influence on the position of equilibrium; they are commonly grouped together, for convenience, as *catalysts*—a term used to conceal our present lack of knowledge of the mode of action of the majority of them. In some cases it is known that the catalytic agent acts merely as a solvent, hence producing its characteristic effect; as examples, we

[1] There is a relation between the explosibility of such metastable gaseous mixtures and the heat change accompanying their reaction.

[2] There is of course in principle absolutely no difference between a reaction and a transformation, the latter including the processes of fusion, sublimation, and vaporization as well as the change from one crystal form to another; all are amenable to the same thermodynamical reasoning. The only differences are in the number of components, which cause corresponding differences in the equations expressing the relations quantitatively, the qualitative relations being deducible from the phase rule.

[3] Doelter (*Handbuch Mineralchemie*, I [1912], 604) estimates the influence of pressure on speed of crystallization to be great for the reason that crystallization is hastened by shaking or knocking; this inference, however, is incorrect, because he fails to distinguish between uniform and non-uniform pressure, attributing to the former effects which could only be produced by the latter.

have the use of sodium tungstate in accelerating the reciprocal transformations of the forms of silica, and the effect of water on mixtures of calcite and aragonite—and still more, of water containing carbon dioxide, in which the solubility is greater—in converting aragonite into calcite at 100° or lower, whereas in the dry state the rate of conversion is not appreciable until temperatures around 400°. The action of many catalytic agents is known to depend upon the formation of unstable intermediate products, but for a very large number the mechanism of their action is still unknown.

It is essential, then, that we bear in mind, on the one hand, the distinction between the theoretical state of equilibrium and, on the other hand, that actually attained under a given set of conditions together with its dependence upon the rate of reaction under those conditions. Indeed, we may say that in a very large number of cases the reaction velocity is the decisive factor in determining the final state, though of course the *direction* in which the reaction proceeds is determined by the energy relations, under the specific conditions of the experiment, of the various substances involved.

Enantiotropic transformations.—Enantiotropic transformations are those in which equilibrium can be attained from either side, and mark the transition of one perfectly stable form into another. The rate of transformation varies enormously from one substance to another, or for a single substance even from one transformation to another. As an illustration take the substance silica:[1] quartz, when heated to 575° goes over quite sharply into another form (β-quartz), but both its transformation to tridymite at or near the inversion point (870°), and the change of the latter to cristobalite at 1,470°, proceed very slowly. There is as yet no means of prognosticating the rate of transformation; except that one may hazard the general statement that, for any single substance, those inversions which are accompanied by the slightest changes of crystal form tend to proceed most rapidly, while the rate of transformation is small wherever the change of crystal form is large.

The temperature at which an enantiotropic transformation takes place is always perfectly definite, although it may appear to lack definiteness when equilibrium is established only slowly; it is

[1] C. N. Fenner, *Jour. Wash. Acad. Sci.*, II (1912), 471.

affected by the presence of impurities if the system is homogeneous, and by uniform pressure, this effect being altogether analogous to that observed with melting-points, and subject to the same thermodynamical formulation. So far as we are aware, no experimental study has been made of the influence of uniform pressure on the transition point of any system solid-solid of direct geological interest;[1] but if the appropriate data were known, this effect could be calculated with sufficient exactness from the equation

$$\frac{\Delta T_2}{\Delta P_2} = \frac{T(V_\beta - V_\alpha)}{41{\cdot}30\,Q}$$

whereby ΔT_2, the change of transition point produced by a change of pressure, ΔP_2 (reckoned in atmospheres), is expressed in terms of Q, the heat of transformation in calories per gram, T, the temperature of transformation at 1 atm., and V_α and V_β, the respective volumes (in c.c.) of 1 gram of substance before and after the transition at T. Unfortunately, however, the requisite data, especially the values of Q, are known in very few instances, and are altogether lacking for the inversions of geologic significance. It is perfectly obvious, therefore, that one may just as well guess the final result as calculate it from the formula, using *assumed* values of the constants involved.

In passing, it may be observed that there is no general parallelism between Q and the volume change $\Delta V = (V_\beta - V_\alpha)$. Thus potassium bichromate has an inversion point at about 240°, accompanied by a large volume change but by only an inappreciable heat effect.[2] On the other hand, during the inversion of cuprous sulphide at 79° considerable heat is evolved, and yet ΔV is only about 0.0001 c.c. per gram.[3]

[1] The effect of pressure on the equilibrium between the various solid forms of water has been investigated by Bridgman (*Proc. Am. Acad.*, XLVII [1912], 441; *Z. anorg. Chem.*, LXXVII [1912], 377); the case of sulphur, which was studied by Tammann (*Krystallisieren und Schmelzen*), is discussed in most textbooks. Some observations have also been made on the effect of pressure on liquid-crystalline transformations, which, however, resemble melting-points much more than they resemble any transitions of geologic interest.

[2] Mitscherlich, *Pogg. Ann.*, XXVIII (1833), 120.

[3] Hittorf, *ibid.*, LXXXIV (1851), 1; Tammann, *Krystallisieren und Schmelzen* (Leipzig, 1903), p. 40.

Transformation points solid-solid are presumably not affected by unequal pressure,[1] which is equivalent to a shearing stress; in this respect they are unlike melting-points. For where melting occurs, the pressure will be greater on the solid than on the liquid phase, owing to the flowing-away of the latter; at transformation points, on the other hand, where both are solid phases, they must be equally subject to the pressure, and therefore the comparatively *large* effects produced by unequal pressure on melting-points will be absent at inversion points.[2] Nevertheless it is entirely probable that persistent unequal pressure (differential stress) might increase the rate of inversion $\alpha \rightarrow \beta$, the latter being the form normally stable at high temperatures; for it is conceivable that unequal pressure in sufficient amount should lower the melting-point of the α-form to such a point that an actual progressive melting[3] of α takes place followed by a crystallization to the β-form, if that were the form stable under these particular conditions.

To illustrate, there are a number of metastable forms (for example, yellow HgI_2 at temperatures below *ca.* 120°, yellow PbO below *ca.* 550°) which can be changed into the corresponding stable forms merely by scratching or rubbing in a mortar.[4] This mode of action of unequal pressure recalls that of catalytic agents, and may be used to aid in accounting for the fact that metamorphic processes occurred easily in those regions which have been exposed to stress.

Enantiotropic transformation of mix-crystals.—We must call special attention to a circumstance which is often neglected although it is of great importance in petrogenetic systems: namely, that the temperature of an enantiotropic inversion has a single definite value only when both the forms involved in the equilibrium are

[1] The idea of "unequal pressure" and its consequences are discussed more fully in a later paragraph.

[2] Nevertheless, there might be some comparatively slight effect; for if the process of transition occurred through a melting (as is outlined in the next sentence in the text), the *difference* between the effects of such unequal pressure on the melting-points of the α and β forms would be its net effect in changing the temperature of inversion.

[3] By this it is not meant that the whole of α should at any instant be melted; see a later paragraph.

[4] It is of course possible that the slight local rise of temperature produced by grinding also plays a subsidiary role in this process.

simple phases and not mix-crystals (solid solutions). This same reservation holds for melting-temperatures, and is there well known. When a mix-crystal of the α-form undergoes enantiotropic change into a mix-crystal of the β-form, there is in general a *temperature-interval* in which the α and β forms may coexist in real equilibrium. As the temperature changes within this region, there is a continuous change in the composition of the mix-crystals, which are in equilibrium with one another, precisely as in the melting of mix-crystals or the distillation of binary liquid mixtures, and for the same reason.[1] The position of this temperature interval is dependent upon the composition of the possible solid solutions, and may be displaced considerably if the corresponding inversion temperatures of the end-members of the series of mix-crystals are far apart.

As an illustration consider the system HgI_2-$HgBr_2$ and its inversion tetragonal→orthorhombic.[2] At 127° red tetragonal HgI_2 changes into yellow orthorhombic HgI_2; $HgBr_2$ is known only as the white orthorhombic form, so that the inversion point of the tetragonal form, if it exist at all, must be at a low temperature. From melts containing both components there separate out a continuous series of orthorhombic yellowish-white mix-crystals ($n\ HgI_2 \cdot m\ HgBr_2$); but the mix-crystals containing little $HgBr_2$ invert at low temperatures into a tetragonal modification. The temperature at which this inversion begins is lower the richer the mix-crystals are in $HgBr_2$; hence the reason that mixtures rich in $HgBr_2$ exhibit no inversion point is in all probability that the velocity of transformation at the equilibrium temperature—which then must be below 0°—is inappreciable. When a mix-crystal of the composition 9.5 mol. per cent $HgBr_2$, 90.5 mol. per cent HgI_2, is cooled slowly (care being taken that the rate of transformation is sufficiently great), it begins about 80° to change to the tetragonal form, producing tetragonal crystals approximately of the composition 2.6 mol. per cent $HgBr_2$, 97.4 mol. per cent HgI_2. Further

[1] See papers by N. L. Bowen, *Am. Jour. Sci.*, XXXIII (1912), 561; "The Melting Phenomena of the Plagioclase Feldspars," *ibid.*, XXXV (1913), 577.

[2] W. Reinders, *Z. physik. Chem.*, XXXII (1900), 494; P. Niggli, *Z. anorg. Chem.*, LXXV (1912), 161.

cooling is accompanied by a progressive change of the orthorhombic into the tetragonal form with a corresponding alteration of composition of the mixtures in both modifications, until finally at about $-20°$ the system is completely transformed into tetragonal mix-crystals of the composition 9.5 mol. per cent $HgBr_2$, 90.5 mol. per cent HgI_2. Thus at temperatures between $+80°$ and $-20°$ (under ordinary pressure) mix-crystals of the above composition represent an equilibrium between two modifications of different composition, either of which is completely stable in presence of the other.

Now among the minerals of geologic importance there are many which are to be considered as solid solutions; from the foregoing, therefore, one must speak not of the inversion *temperature* of any such mineral which exists in more than one form, but only of the inversion interval. For instance, if the relation between augite and hornblende should prove to be enantiotropic (at present the nature of their relation is unknown), they could coexist in *true equilibrium* throughout a range of temperatures. It would therefore be incorrect to speak of a definite temperature, or a definite pressure, of transformation of these important minerals.

Furthermore, the modifications which coexist in equilibrium under any particular set of conditions will not have the same chemical composition. As a matter of fact, such differences have been observed in gabbros from Katéchersky by L. Duparc,[1] who gives the following analyses:

	Augite	Amphibole
SiO_2	50.91	43.34
Al_2O_3	2.64	12.60
Fe_2O_3	.....	10.44
FeO	10.07	7.92
MnO	0.41	.....
CaO	23.33	12.91
MgO	13.30	12.52
K_2O	Not determined	0.24
Na_2O	Not determined	1.90
	100.66	101.87

[1] *Bull. soc. franc. min.*, XXXI (1908), 50. Analogous observations have been made by L. J. Wild, *Trans. New Zealand Inst.*, XLIV (1912), 333; also by J. B. Harrington, *Geology of Canada* (1879), p. 21.

The augites were considerably "uralitized" (transformed into fibrous hornblende, appearing as pseudomorphs of the augite), the process being accompanied by a marked change of composition. This interpretation of the process presupposes equilibrium conditions; but whether equilibrium conditions obtained or not, this example may serve to point out the possibility of the actual occurrence of such differences.

Closely related to the phenomena of transformation of mix-crystals is the phenomenon of allotropy, according to the latest views, which so far are the only views which aid us materially in correlating this property with other properties of the substance.

The phenomenon of allotropy.—It is well known that wherever a substance exhibits polymorphism, its various allotropic modifications may be obtained from a solution or fusion merely by varying the conditions of crystallization (e.g., rate of cooling, concentration of solvent). On this fact as foundation, a theory of allotropy has been developed by Smits,[1] the basic idea of which is that the different modifications are in reality all present in equilibrium with one another in the solution, the appearance of any one form in the solid state being determined by the conditions of this internal equilibrium, the position of which in turn is affected specifically by the solvent medium.

Let us consider, for the sake of simplicity of statement, that no foreign solvent is present, that the liquid phase is a melt of the pure substance. Such a liquid phase, which hitherto has been generally supposed to be unary (containing only a single molecular species), is considered by Smits to be pseudo-unary; that is, it contains two (or more) pseudo-components in mutual equilibrium. As a necessary consequence of the internal equilibrium in the liquid phase it follows that there is equilibrium in the solid phase between the same pseudo-components; the position of this equilibrium is, of course, not identical with that of the equilibrium in the liquid phase (just as in the case of mix-crystals). In other words, when an apparently unary liquid solidifies, even although the cooling goes on in such a way that equilibrium between the pseudo-components obtains continuously, the solid phase separating out is not a pure pseudo-component but is itself a pseudo-unary system in internal equilib-

[1] A. Smits, *Z. physik. Chem.*, LXXVI (1911), 421, and later papers in 1912 and 1913, especially *ibid.*, LXXXII (1913), 657.

rium and therefore is a mix-crystal. The solid forms actually known to us are not the pure pseudo-components themselves, but are solid phases in an equilibrium which is displaced by external circumstances toward one side or the other. The displacement of equilibrium in the solid phase produced by change of external conditions may proceed until unmixing supervenes, i.e., until an inversion point is reached.

This theory has already justified itself as a working hypothesis at least; it has enabled Smits to co-ordinate certain phenomena and hence in part to predict the behavior of certain systems. This success indicates the great probability of the existence of internal equilibria, and in this respect it is in complete harmony with a number of other lines of evidence. It leads us to look upon a single crystal, not as a simple body, but as a more or less complicated configuration the behavior of which depends on the state of equilibrium within the crystal.

Moreover, it possesses a great advantage as compared with the old point of view in that it affords a clue to the problem of the apparently arbitrary appearance of metastable modifications. For if we know the diagram of such a pseudo-unary system—that is, if we know the equilibrium lines in both the liquid and the solid phase as well as the mix-crystal and liquidus curves—we can foretell which factors will promote, or hinder, the formation of a given metastable product. For instance, if the speed of attainment of equilibrium is small and the temperature change is rapid, the equilibrium will not have time to adjust itself to the changing conditions; unmixing therefore will occur at a composition (with respect to the pseudo-components) and at a temperature which differ from those corresponding to continuous real equilibrium—in other words, the resultant products in the two cases are different. The position of the various equilibrium lines and the rates at which the various equilibria are established under the particular conditions are, in short, the factors that determine which product actually appears. Hitherto the only aid in the prediction of what would appear has been that derivable from the so-called Ostwald rule,[1] a

[1] The rule, as stated by Ostwald, is: In all reactions the most stable state is not straightway reached, but the next less stable or that state which is the least stable of the possible states. It may be observed that this alternative mode of statement insures the validity of the rule in a large number of cases.

rule to which there are very many exceptions. From the above we see that the rule—in spite of its breadth—will not be generally applicable; for if it were, it would imply limitation of the type of possible configuration of the diagram of state, whereas there is no reason to believe that such limitations exist.

From this point of view also we can see how the phenomena of monotropy and of allotropy are related. Whether one or the other of these phenomena occurs depends again on the position of the lines representing the internal equilibrium, especially in relation to the unmixing curves.

The foregoing brief account of the theory of allotropy proposed by Smits has been given mainly for the purpose of bringing one point to the attention of geologists and mineralogists: namely, that it aids in familiarizing us with the idea that pure phases (even crystalline) are not necessarily made up of a single molecular species, an idea which is supported by a considerable array of facts and is in conflict with no direct experimental evidence. In addition, it indicates that even metastable states, the existence of which has often been looked upon as a proof of lack of complete validity of physico-chemical principles, may also be treated theoretically.

Monotropic transformations.—Monotropic changes are irreversible; they occur when a form which is metastable under the particular conditions passes over into a form which is essentially stable under those conditions of temperature and pressure. Monotropic changes therefore occur whenever the rate of transformation becomes appreciable; moreover, since this rate is different under different conditions, the transition temperature is not a definite point but may lie within a very wide range. As an illustration consider the two principal forms assumed by calcium carbonate. All the evidence indicates that aragonite is metastable at temperatures above the ordinary; yet in the dry state it does not go over into calcite until about 400°. Yet the transition to calcite—which, being more stable, has at any definite temperature a lower vapor pressure and (in any single solvent) a smaller solubility than aragonite—takes place very slowly at 100° in presence of water, and more rapidly and at a lower temperature in presence of water containing

carbon dioxide; for carbon dioxide increases the solubility of both forms, and hence the rate of transformation.[1]

The occurrence of a real monotropic change implies that one modification of the substance involved is altogether metastable throughout its range of existence.[2] But we may have inversions which appear to be monotropic, but are in reality delayed enantiotropic changes; in such cases both forms of the substance have stable fields of existence, the apparent monotropy being due entirely to the sluggishness of transformation. A good example of this is shown in the silica diagram, as determined by Fenner.[3] Quartz, when heated in presence of a suitable flux, goes over slowly into tridymite at about 870°,[4] and the change is reversible; but when the quartz is heated without a flux, it goes over into β-cristobalite, the temperature at which this transformation occurs (about 1,400° or higher) varying with the rate of heating. β-cristobalite on cooling, in absence of a flux, does not return to quartz (or go over into tridymite), but at a temperature around 200° is transformed into α-cristobalite, which therefore at ordinary pressure must be altogether metastable. Thus transformations which are sluggish may appear to be monotropic until by the choice of an appropriate solvent medium their rate is so increased that their true character can be ascertained.

The temperature at which a monotropic change takes place can be influenced only by those factors which affect the rate of transformation; it will therefore be affected by the presence of impurities when the latter can act as fluxes and in this way increase the rate, but it will be unaffected by uniform pressure, because uniform pressure apparently has little or no influence on the rate of reaction, even where the reaction is attended by a large volume change. In

[1] It is to be observed that this argument of an increased solubility being attended by an increased rate of reaction must be used with caution; it will in general hold only when the original solubility was comparatively small.

[2] At least, at ordinary pressure. At higher pressures such a modification may have a stable field of existence; though up to the present there is no direct experimental evidence bearing on this point.

[3] *Jour. Wash. Acad. Sci.*, II (1912), 471. The system silica has also been investigated by Endell and Rieke, *Z. anorg. chem.*, LXXIX (1912), 239, and by Endell and Smits, *ibid.*, LXXX (1913), 176.

[4] This is the lowest temperature at which this transformation will take place. It occurs at all temperatures up to 1470°, at which point tridymite ceases to be the stable phase and is replaced by β-cristobalite.

accordance with this we have observed that a pressure even of 15,000 atmospheres (equivalent to a depth of perhaps 30 miles) is incompetent at room temperature to convert marcasite (sp. gr. 4.9) into pyrite (sp. gr. 5.0) nor did this change take place to an appreciable extent at 425° under 2,000 atmospheres pressure, although under ordinary pressure it does take place about 450°.[1]

Geologic thermometer.—The use of transformation and other points has been suggested as fixed points on a geologic temperature scale,[2] that is, as points of reference by means of which we may be enabled to fix the range of temperature within which certain processes have occurred or certain rocks or minerals have been formed. Such points should be chosen and used with caution. The only points free from objection are those transformations solid-solid which take place at a definite point with appreciable velocity and are not much influenced by pressure; in other words, we must choose rapid transitions which are accompanied by a small change of volume (or in the rarer case, by a large heat effect; or by both together). This is a serious limitation upon the number of satisfactory points, a limitation which must, however, be retained so long as our ignorance of the magnitude and character of the compressive stresses to which rocks have been subject remains complete, as in effect it now is. Melting-points could be used as points on the geologic thermometer only by postulating the purity of the substance and on the further improbable assumption that the compression has always been uniform; for, as we hope to show in a later paragraph, the effect of unequal pressure (shearing stress) upon the melting-point is so great that no conclusion of any value can be drawn except from such transition points solid-solid as remain unaffected by compression of any kind.

The use of transitions involving a gas or vapor phase is altogether indefensible. Take for instance the dissociation of calcium carbonate, according to the equation $CaCO_3 = CaO + CO_2$; to each temperature there corresponds a definite pressure of CO_2, a pres-

[1] G. Spezia (*Atti. Accad. Sci. Torino*, XLVI [1911], 1) has made a number of similar observations all of which are in complete harmony with the above statements.

[2] See Wright and Larsen, *Am. Jour. Sci.*, XXVII (1909), 421; *Z. anorg. Chem.*, LXVIII (1910), 338; J. Koenigsberger, *Neues Jahrbuch Min.*, Beilage Band XXXII (1911), 101, in which he makes a number of statements which require some reservation, as will be evident from what follows in the text.

sure which varies enormously with the temperature. Unequal pressure moreover affects such dissociations to a still greater extent than it influences melting-points. Transitions involving a vapor phase therefore can be employed as reference points when, and only when, we can accurately define the character and magnitude of the compression—a condition unlikely to be fulfilled in any instance of geologic importance at any time in the immediate future.

Occurrence of reactions in systems solid-solid.—This subject has been treated at some length in a recent communication from this laboratory;[1] so only the general conclusions will be presented here. Reaction may proceed at the surfaces of contact of adjacent grains of the constituents; but it by no means follows that reaction occurs in all systems where we might on other grounds judge that the stable state of the system would be that which obtains after reaction has taken place. The extent of the reaction will be increased by renewal of the surfaces of contact, and this may be effected by any agency which produces a kneading or grinding of the mass. Hence the reaction will be furthered by application of non-uniform (unequal) pressure (or in other terms, shearing stress), which moreover may also act in another way, the net result of which, however, is again to bring together new surfaces of contact. This will happen, namely, if the unequal pressure is of such character as to cause any of the original constituents or of the products of reaction to melt at the temperature of experiment; for then it will obviously further the reaction. Furthermore, non-uniform pressure can promote reaction by bringing adjacent grains into good contact; the reaction can then progress by diffusion across the area of contact. The effect of uniform pressure on reaction between solids is limited to this rôle, and therefore its effect is in general slight.

Interdiffusion of solids is appreciable in some systems: for instance, gold traveled into lead some 7 mm. in four years at room temperature, and about as far in as many weeks at 160°.[2] All the evidence indicates, however, that interdiffusion goes on only in

[1] J. Johnston and L. H. Adams, *Am. Jour. Sci.* (4), XXXV (1913), 205; *Z. anorg. Chem.*, LXXX (1913), 281.

[2] Roberts-Austen, *Phil. Trans. Roy. Soc. London*, A., CLXXXVII (1896), 383. For full information on this subject see "Report on Diffusion in Solids" by C. H. Desch, *British Assoc. Report* (Dundee, 1912); see also the recently published *Geologische Diffusionen* by R. E. Liesegang (Dresden: Steinkopf, 1913).

those systems in which solid solutions can form, as indeed one might expect a priori. The diffusion is enormously accelerated by rise of temperature, and may be influenced by pressure, though it would be premature to regard this as established yet, far less to generalize from it. In any case the rate of diffusion under geologic conditions, wherever diffusion is possible at all, is probably sufficient to reduce in the course of geologic time the degree of heterogeneity of systems which originally were not too coarse grained. Nevertheless old rocks frequently show well-defined layers of isomorphous crystals which, so far as we know, can form homogeneous mix-crystals; this is true especially for plagioclases, hornblendes, augites, and garnets, and indicates that in these cases the rate of diffusion is vanishingly small.

EFFECTS OF TEMPERATURE AND PRESSURE ON SYSTEMS SOLID-FLUID

General considerations.—In discussions of the change of volume (to take a specific instance) which accompanies the process of melting, one often encounters the argument that this change is given by the difference between the densities of the crystals and of the glass, as measured at ordinary temperature. This argument may be altogether misleading, because it involves the tacit assumption that the expansion coefficients of both crystals and glass are identical—an assumption which certainly can fit the facts only in a few exceptional cases.[1] Of course until the necessary quantities have been actually determined, one can only use the densities observed under ordinary conditions; but if one does so, the limitations of any results calculated in this way must be recognized, and the conclu-

[1] The truth of this statement is perhaps more obvious from the following mathematical formulation. If V_l and V_s are the specific volumes of glass and crystals, respectively, at ordinary temperature, the change of volume

$$\Delta V = V_l - V_s .$$

The change of volume at the temperature t is

$$\Delta V_t = (V_l + \Delta V_l) - (V_s + \Delta V_s)$$
$$= \Delta V + (\Delta V_l - \Delta V_s)$$

where ΔV_l and ΔV_s are the expansion produced by the increased temperature in glass and crystals, respectively. The term $(\Delta V_l - \Delta V_s)$ may be positive or negative, and might even be of such magnitude as to cause the sign of ΔV_t to be opposite from that of ΔV, if the latter were itself small.

sions regarded as tentative and preliminary only. Precisely similar remarks apply to the effect on this volume change of pressure alone or of pressure and temperature combined.

The computation of heats of reaction for conditions differing from those under which the experimental values were determined is subject to altogether analogous limitations, the specific heat, or change of heat capacity, being the exact analogue of expansion coefficient. In this case indeed we may have—although to be sure the experimental data are not very concordant—an instance of reversal of the heat effect of a reaction with rise of temperature. The heat of transformation aragonite → calcite at 20° is small, probably positive and less than 1 cal. Now according to the most thorough series of measurements for aragonite and calcite,[1] their mean specific heats within the range 0°–300° (the limit of the measurements) are respectively 0.2246 and 0.2204; hence the difference is 0.004 per degree or about 1.8 cal. for 450°. Therefore the heat of transformation at 470° will be 1.8 cal. *less* than it is at 20°, and thus a minus quantity; this is in agreement with the observations of Lashchenko,[2] who concluded that this transformation at 470° is accompanied by the absorption of considerable heat.

Variation of effects of compression with its character.—There is a marked difference in the effect of compression according as it is uniform or otherwise. Changes in the physical properties of substances are induced by uniform pressure, but disappear when the pressure is removed. Non-uniform compression produces permanent deformation of bodies exposed to it, and therefore causes permanent alterations in many of the physical properties of the substance. The effects of the latter differ so much from, and so far outweigh those of uniform pressure, both in character and in magnitude, that it is advisable to treat them separately.

Uniform pressure is, by definition, the same in all directions; in practice, however, this is not altogether easy of attainment at really high pressures, because then the liquids generally used to

[1] Lindner, *Sitzber. physik. medizin. Ges. Erlangen*, XXXIV (1902), 217.

[2] Lashchenko, *Jour. Russ. Phys. Chem. Soc.*, *XLIII* (1911), 793. It may be noted, however, that Boeke, who used a differential method, concluded that the heat change at 470° is less than 0.5 cal. (*Z. anorg. Chem.*, *L* [1906], 246).

transmit pressure become exceedingly viscous.[1] A non-uniform compression may always be resolved into a shearing stress and a (smaller) uniform pressure, the former being the preponderating factor in producing the results observed. Now a consistent account of all the experimental work can be given if we make the plausible assumption that the shearing stress acts on the solid phase, but not on the liquid phase; in accord with this, in non-uniform compression the liquid (fluid) phase would be subject to less pressure than the solid phase, whence the name "unequal pressure" chosen to designate this type of compression.[2]

EFFECT OF UNIFORM PRESSURE ON MELTING-POINTS

Thermodynamical considerations lead directly to the differential equation

$$\frac{dT}{dp} = \frac{T dV}{\Delta H} \qquad \text{(I)}$$

which expresses the change of melting-point (dT) with change of pressure (dp) in terms of T, the absolute temperature of melting, dV, the volume change and ΔH, the heat change which accompanies melting of the substance at T. Before this equation can be applied it must be integrated, since we are dealing with finite changes.

In order to integrate this equation rigorously it is necessary to know how dV and ΔH vary with pressure and temperature. The exact magnitude of these variations is not known in general; but, fortunately, their effect is slight and may for most practical purposes be neglected. We may consequently use the following form of the equation to calculate the change of melting-point (ΔT_2) produced by a change of pressure (ΔP_2, expressed in atmospheres[3]):

$$\frac{\Delta T_2}{\Delta P_2} = \frac{T(V_l - V_s)}{41{\cdot}30\, Q} \qquad \text{(II)}$$

[1] For instance, at 20,000 atm. and ordinary temperatures, even gasoline becomes quite viscous (approximately, perhaps, of the consistency of vaseline).

[2] A fuller discussion of this topic, together with many references to previous work, will be found in a paper by Johnston and Adams, *Am. Jour. Sci.* (4), XXXV (1913), 205; *Z. anorg. Chem.*, LXXX (1913), 281; cf. also *postea*.

[3] That is, true atmospheres (1,033 g. per sq. cm.).

wherein Q is the heat (absorbed) of melting in calories per gram, and V_l and V_s the respective volumes of 1 gram of substance at the melting-point in the liquid and the solid state. An example of the agreement between calculation from this formula and actual observation of the effect of pressure on the melting-points of tin, bismuth, cadmium, and lead is afforded by the following table, taken from a former paper from this laboratory;[1] the divergences are such as are to be expected in view of the present uncertainty in the values of Q, the latent heat of melting:

TABLE I

EFFECT OF UNIFORM PRESSURE ON THE MELTING-POINTS OF CERTAIN METALS

Metal	Latent Heat cal. per gram Q	Vol. Change on Melting $V_l - V_s$	ΔT per 1,000 atm. calc. from Equation II	ΔT per 1,000 atm. observed
Sn.....	14.25	0.003894	+3.45	+3.28
Cd.....	13.7	0.00564	+6.10	+6.29
Pb.....	5.37	0.003076	+8.59	+8.03
Bi.....	12.6	−0.00342	−3.67	−3.55

Equation II enables us therefore to calculate the effect of uniform pressure on melting-point if certain physical constants of the material are known; unfortunately, however, these constants are known for very few substances, among which are practically none of direct geologic interest.

Direct determinations of the effect of pressure on melting-point have been made only as follows: potassium,[2] sodium,[3] mercury,[4] water,[5] and a large number of organic substances[6] (e.g., benzol, phenol, naphthalene, etc.) including several substances capable of existence as a liquid-crystalline phase.[7] All of these

[1] Johnston and Adams, *Am. Jour. Sci.*, XXXI (1911), 516; *Z. anorg. Chem.*, LXXII (1911), 29.

[2] Tammann, *Krystallisieren und Schmelzen.* [3] *Ibid.*

[4] P. W. Bridgman, *Proc. Am. Acad.*, XLVII (1912), 349; *Z. anorg. Chem.*, LXXVII (1912), 377.

[5] *Proc. Am. Acad.*, XLVII (1912), 441.

[6] Tammann, *loc. cit.;* Hulett, *Z. physik. Chem.*, XXVIII (1899), 629 (pressures only up to 300 atm.).

[7] Hulett, *loc. cit.;* Körber, *Z. physik. Chem.*, LXXXII (1913), 45.

investigations show that the change of melting-point for the first 1,000 atm. is less than 40°;[1] further, that for each succeeding 1,000 atm. the effect is progressively less, a fact which indicates that no maximum melting-point is realizable (if indeed it is possible).

There are only two substances for which a lowering of melting-point by uniform pressure is established, namely, water and bismuth; and with water only at pressures up to about 2,100 atm. (where the m.p. is −22°), above which the melting-point rises steadily with pressure, reaching +76° at 20,000 atmospheres. There may be a few other substances belonging to this category but their number is certainly small. In general, therefore, uniform pressure raises the melting-point; so that we may say that uniform pressure increases the rigidity of material—an increase which becomes very noticeable with substances (e.g., the oils commonly used to transmit pressure) whose freezing-point is not far removed from the ordinary temperature.

EFFECT OF UNIFORM PRESSURE ON SOLUBILITY

The influence of temperature upon the solubility of solids varies greatly from one substance to another; the more common effect is an increase of solubility with temperature, but there is a large number of substances (e.g., $Ca(OH)_2$, $CaSO_4 2H_2O$, to name two common ones) whose solubility decreases with rise of temperature. The direction and magnitude of this change of solubility is determined by the sign and magnitude of the heat of solution; an absorption of heat corresponds to an increase of solubility with temperature, an evolution of heat to a decrease. In applying this criterion, one must take care to choose the heat effect[2] appropriate to the dissolution of the particular solid phase which is in equilibrium with the solution under the particular conditions; for instance, to use the heat of solution of $Ca(OH)_2$, not of CaO, and at temperatures

[1] With one exception, camphor, where 300 atm. pressure raised the melting-point by 38.7° (Hulett, *loc. cit.*).

[2] The heat effect to be used is always that observed when 1 mol. of the solid is dissolved in a large volume of a solution nearly saturated with respect to the solid in question.

above 32.4° to use the (positive) heat of solution of Na_2SO_4 (anhydrous), at lower temperatures the (negative) heat of solution of $Na_2SO_4 10H_2O$ which is then the stable solid phase in solution.

The effect of uniform pressure on the solubility of solids can be calculated from an equation analogous to equation I whenever the heat effect and volume change appropriate to the particular conditions are known. Hitherto trustworthy direct determinations have been made for only four substances,[1] of which but one is even of indirect geological significance; the mean values obtained are given in the subjoined table.

TABLE II

CHANGE OF SOLUBILITY PRODUCED BY UNIFORM PRESSURE (COHEN AND COLLABORATORS)

PRESSURE IN ATMOSPHERES	$CdSO_4/_3H_2O$ AT 25°		$ZnSO_4 \cdot 7H_2O$ AT 25°		MANNITE AT 24.05°		NaCl AT 24.05°	
	Conc. of Satd. Solu. g. $CdSO_4$ per 100 g. H_2O	Percentage Change	Conc. of Satd. Solu. g. $ZnSO_4$ per 100 g. H_2O	Percentage Change	Conc. of Satd. Solu. g. Mannite per 100 g. H_2O	Percentage Change	Conc. of Satd. Solu. g. NaCl per 100 g. H_2O	Percentage Change
1....	76.80	.....	57.95	.....	20.66	.....	35.90	.....
500....	78.01	+1.57	57.87	−0.14	21.14	+2.32	36.55	+1.81
1,000....	78.84	+2.68	57.65	−0.52	21.40	+3.57	37.02	+3.12
1,500....	.....	.....	.....	.....	21.64	+4.72	37.36	+4.07

From this we see that it would be likely to require a very considerable change of (uniform) pressure to change the solubility by 50 per cent, a change which may easily be produced by a comparatively small change of temperature. Hence the influence of pressure on the solubility of solids is altogether negligible in comparison with the influence of temperatures.

Uniform pressure may cause marked increase in the apparent solubility in certain cases; namely, wherever we are really dealing with an equilibrium, the state of which is displaced by pressure. An example of this is afforded by calcium carbonate in presence of water and carbon dioxide; increased pressure increases the concentration of CO_2 in the water (and hence really changes the character

[1] E. Cohen and L. R. Sinnige, *Z. physik. Chem.*, LXVII (1909), 432; LXIX (1909), 102; E. Cohen, K. Inouye, and C. Euwen, *ibid.*, LXXV (1911), 257. These authors give a critical résumé of earlier work along this line.

of the solvent) and thus produces a greater apparent solubility of the $CaCO_3$. Moreover, the solubility of solids in fluids at temperatures above the critical point of the solution will be dependent on the pressure, since the effect of the latter is then to change the concentration of the solvent, just as pressure affects the solubility of gases, by changing the concentration of the solute itself, and hence the concentration of the solute in the solution.[1]

One point remains to be noticed, namely, that in making use of solubility data we must remember that solubility, and the heat effect and volume change accompanying dissolution of a substance, are affected by the presence of other substances[2] in the solvent. Now from a complex solution from which any one of a number of substances can conceivably separate out first, the product which actually separates out is that which under the particular actual conditions is least soluble, or has reached its limit of saturation.[3]

Solubility relations are therefore of the highest importance; but they must always be determined under the proper conditions, and cannot be inferred from the relative solubilities of the various substances in pure water.

Importance of solubility relations in determining the course of a reaction in solution.—The importance of this fact—that solubility (or perhaps we should rather say, lack of solubility) is the predominating factor in determining the order of separation of the products of reaction of any system—is not so universally appreciated as it ought to be. The appearance of any one product is very often ascribed to the existence of a greater affinity between its component parts than exists between the components of the other compounds which might conceivably be formed by the reaction. In a certain sense this is true, but in the sense in which the term

[1] This question is discussed later.

[2] The following are two extreme examples, which illustrate the two main modes of action of added substances. $Ag(CN)_2$ is very sparingly soluble in water, but quite soluble in water containing KCN, owing to the formation in this case of the complex $KAg(CN)_2$. The solubility of AgCl, on the other hand, is much smaller in water containing KCl (or $AgNO_3$), owing to the effect of the common ion Cl' (or $Ag+$).

[3] This is the basic principle underlying van't Hoff's great series of investigations of the oceanic salt deposits.

affinity is ordinarily employed it is fallacious and misleading. For example, consider the following reactions:

$$AgNO_3+BaCl_2 = 2AgCl+Ba(NO_3)_2$$
$$Ba(NO_3)_2+Ag_2SO_4 = BaSO_4+2AgNO_3$$

From the first of these, we should, according to the above reasoning, conclude that silver was a stronger base than barium; while from the second, we reach the directly opposite conclusion.

As another example, take the statement (which appears in the majority of textbooks on organic chemistry) that tetramethylammonium hydroxide ($N(CH_3)_4OH$) cannot be displaced from aqueous solutions of its salts (e.g., the chloride) by potassium hydroxide because the former is the stronger base. But it has been shown that if we choose a medium (methyl alcohol) in which one of the products (potassium chloride) of the reaction is insoluble, the reaction

$$N(CH_3)_4Cl+KOH = N(CH_3)_4OH+KCl$$

takes place and yields practically the theoretical amount of the tetramethylammonium hydroxide.[1] These two examples, which are typical of a very large number of similar cases, demonstrate that the relative strength of the competing acids and bases is a negligible factor in determining the product which separates out following a reaction in aqueous (or other) solution; the important factor is the relative solubility limits of the original substances and of the possible products of reaction.[2] This behavior is in thorough accordance with the law of mass action and with the currently accepted theory of solution; so that if we knew the solubility relations of all possible products (including complex salts, e.g., the double cyanides and oxalates, if such are possible) we could predict quantitatively the course of the reaction.

Another good example, which at the same time illustrates another point, is this. If we add hydrochloric acid to a solution of sodium silicate, sodium chloride will be formed and silicic acid (in

[1] Walker and Johnston, *Jour. Chem. Soc.*, LXXXVII (1905), 955.

[2] This statement is subject to slight limitations, which, however, are of minor importance, and hence need not be discussed here. Their effect is such that a lack of concordance of 1 or 2 per cent may be found between theory and practice.

the form of gelatinous silica) liberated; but yet at a very high temperature, as in the process of glazing earthenware, silicic anhydride in presence of water vapor is capable of decomposing sodium chloride with expulsion of hydrochloric acid. This behavior is not at first sight dependent on solubility relations; but it is perfectly analogous if we consider that volatility may be looked upon as solubility in a vacuum as solvent. We can therefore extend the statement of the preceding paragraph and say that the factor which determines the result of heating together a number of substances at high temperatures is lack of solubility or of volatility, the substance which tends to appear being that which under the particular equilibrium conditions is least soluble or least volatile.

THE LAW OF MASS ACTION AND THE REACTION CONSTANT K

Consider the reversible chemical action

$$A+B \rightleftarrows C+D$$

where the letters represent single molecules of the substances as in ordinary chemical formulae. Then according to the law of mass action the state of equilibrium of the above system is determined by the equation[1]

$$\frac{[A][B]}{[C][D]}=K$$

where the symbols [A], [B], etc., represent the "active masses" *at equilibrium* of the respective substances; K is a constant, the value of which depends solely on the external conditions (e.g., temperature) but is independent of the total amount of material present. When the reaction takes place in a wholly gaseous system, the active mass of each substance is proportional to its molecular concentration or partial pressure. When the system is an aqueous

[1] When the reaction is $nA+mB \rightleftarrows pC+qD$ (that is, where more than one molecule of any (or all) of the substances enters into the reaction) the expression for the reaction constant is

$$\frac{[A]^n[B]^m}{[C]^p[D]^q}=K$$

In this case attention must be paid to the unit of concentration employed except when $m+n=p+q$, as the numerical value is then dependent on the unit of concentration employed.

solution, the active mass of each reacting molecular species (which are, according to the current views, ions and undissociated molecules) is given by the concentration of that particular species in the unit of volume (expressed always in molecular, or equivalent, concentrations). It should be observed that K is found to be constant only in dilute solutions (and correspondingly, in gaseous systems only at low pressures); but there is no doubt that its lack of constancy at greater concentrations (or pressures) is due altogether to our lack of accurate knowledge of the real concentrations (partial pressures) of the reacting molecular species. The reaction constant K is independent of the amounts of the various substances originally present, so long as the temperature and pressure remain constant; its dependence on temperature (at constant pressure) is given by the equation[1]

$$\frac{d\,ln\,K}{dT}=\frac{Q}{RT^2} \qquad \text{(III)}$$

Hence if we know K at any one temperature, and the heat change Q accompanying the reaction,[2] we can calculate K at any temperature; conversely from the values of K at various temperatures, we can compute mean values of Q.

Similarly, the variation of K with (uniform) pressure, at constant temperature, is given by the equation

$$\frac{d\,ln\,K}{dp}=-\frac{\Delta V}{RT} \qquad \text{(IV)}$$

where ΔV is the increase of volume accompanying the reaction when 1 mol. is transformed. This equation holds strictly in homogeneous systems; where solid substances are present, it is essential that they be subject to the same uniform pressure as the rest of the system. The equation is the quantitative formulation of the statement that increase of pressure tends to displace the equilibrium in the direction in which the reaction is accompanied by decrease of volume.

[1] $ln\,K$ is $\log_e K = 2.303 \log_{10} K$.

[2] For exact work we must know further how Q varies with temperature; the assumption of a constant value of Q, however, leads to results sufficiently exact for most purposes. Further, our knowledge of Q at any one temperature usually leaves much to be desired, not to speak of its variation with temperature.

In a completely fluid system the influence of pressure on the position of equilibrium will not in general be large, because the volume change ΔV is usually small. In gaseous systems the direction of the effect can readily be predicted, since the volume of a gas (at constant temperature and pressure) is a direct measure of the number of molecules of it present. Therefore pressure is without effect if the total number of molecules remains unchanged by the reaction; otherwise, it displaces the position of equilibrium toward the side with the smaller total number of molecules.

In heterogeneous systems liquid-gas and solid-gas the pressure changes the concentration in the gas phase, and in this way may have very considerable effect on the position of equilibrium.

The action of *unequal* pressure, however, on a heterogeneous equilibrium is of an entirely different order of magnitude. If a system solid-liquid or solid-gas is compressed in such a way that the fluid phase can escape continuously, the reaction will be driven in one definite direction. For example, if the system

$$RCO_3 + SiO_2 \rightarrow RSiO_3 + CO_2$$

is compressed in such a way that the CO_2 escapes, $RSiO_3$ will always be formed. Then, too, unequal pressure influences greatly the solubilities of solids, and thus may entirely change the relative concentrations of the solid substances in the fluid phase.

The foregoing paragraphs provide a basis for the observation that metamorphosed rock is usually denser than that from which it was formed, for the so-called *Volumgesetz* of the Germans. To this rule there are many exceptions; the extent to which it holds is about what we might expect; for while pressure tends to produce denser material, it may not actually do so if the rate of reaction is very small under the particular conditions. Moreover, we cannot safely conclude from measurements of specific volume made at ordinary temperature (as all of them hitherto have been) that the change of volume under the actual conditions of transformation was the same in magnitude or even in sign; for, as we have already pointed out, a difference (such as may easily occur) between the coefficients of expansion of the substances concerned may cause a reversal of sign of the volume change, especially when the latter is small.

As an application of the law of mass action to a very simple case, consider the dissociation of calcium carbonate according to the equation

$$CaCO_3 \rightleftharpoons CaO + CO_2 .$$

We will presume that the reaction takes place in the gaseous phase: the equilibrium constant is then given by the equation

$$\frac{(CaO)\,(CO_2)}{(CaCO_3)} = C ,$$

the quantities in parentheses denoting the partial pressure at equilibrium of the substance written within the parentheses.[1] Now CaO and $CaCO_3$ are always present in the solid phase, from which it follows that at any one temperature (CaO) and ($CaCO_3$) are constant; whence we have $(CO_2) = K$. In other words the pressure of CO_2 in equilibrium with a mixture of CaO and $CaCO_3$ is independent of the amounts of the solids present, and has a definite value for every temperature;[2] its variation with temperature being given by equation III.

E. Baur[3] has investigated a system of considerable geologic interest, namely, the reaction

$$SiO_2 + 4HF \rightleftharpoons SiF_4 + 2H_2O$$

which takes place when aqueous hydrofluoric acid is distilled in presence of excess of silica. Under these conditions SiO_2 is solid, the other three substances gaseous; therefore at definite temperature and pressure we should find that the expression

$$\frac{(SiF_4)\,(H_2O)^2}{(HF)^4} = K .$$

[1] It may be objected that it is absurd to talk about the vapor pressure of a substance such as CaO; we have, however, every reason to believe that such pressures, though infinitesimal, are real and perfectly definite. Application of the mass law to the vaporization of CaO, that is, to the reaction CaO (solid) $\rightarrow$ CaO (vapor), gives the relation $\frac{(CaO)}{CaO\ (solid)} = K'$; but since excess of solid is present, CaO (solid) is constant and therefore at constant temperature $(CaO) = K''$.

[2] These values may be found in Johnston, *Jour. Am. Chem. Soc.*, XXXII (1910), 938.

[3] *Z. physik. Chem.*, XLVIII (1904), 483.

The actual determination of the various concentrations is very difficult, so that moderate concordance between the values of K is all that can be expected. At 104°, K is of the order of 2×10^{9}, at 270° it is about 5×10^{7}. This decrease of K with rise of temperature shows that the equilibrium is displaced toward the left by rise of temperature, so that the reaction, as written above, is at these temperatures slightly exothermic. The influence of pressure is easily predicted; for, since we have 3 volumes on the right side, as compared with 4 volumes on the left (the volume of the solid silica is, in comparison, negligible), pressure will displace the equilibrium toward the right-hand side of the equation above. From the above it follows that, when such vapors escape from the magma, lowering of their temperature alone will result in a dissolution, instead of a precipitation, of SiO_2; decrease of pressure, on the other hand, results in the production of quartz—an effect which will presumably predominate over that produced by decrease of temperature, since the volume change is large but the heat change accompanying the reaction comparatively small.

Constant solubility product.—Again we can readily deduce from the mass-action law the experimental fact of the constancy of the so-called solubility product. Thus for the substance AgCl we find that

$$(Ag^{+})\,(Cl^{-})=K$$

where (Ag^{+}) and (Cl^{-}) represent the real concentrations of silver ions and chlorine ions in the solution; K is a constant, depending only upon the temperature. This relation holds true for any solution in which silver ions and chlorine ions may be present together in contact with solid AgCl—no matter what other ions may also be present—provided always that (Ag^{+}) and (Cl^{-}) are understood to be the *real* concentrations of the respective ions, when equilibrium has been attained.

As a specific example of the application of this principle to the determination of equilibrium conditions, we shall consider the reversible reaction

$$BaSO_4+Na_2CO_3 \rightleftharpoons BaCO_3+Na_2SO_4\,.$$

There are present in the system the following molecular species: un-ionized $BaSO_4$ and $BaCO_3$, Ba^{++}, SO_4'', CO_3'' (and Na^{+}, which,

however, may be left out of account, since it plays no direct part in the reaction).

We have then the equilibrium equations between these quantities

$$[Ba^{++}][SO_4'']=K_1 \text{ and } [Ba^{++}][CO_3'']=K_2$$

where K_1 and K_2 are the solubility products of $BaSO_4$ and $BaCO_3$, respectively; and therefore, since $[Ba^{++}]$ is common to both,

$$[SO_4'']/[CO_3'']=K_1/K_2=K\,.$$

In words, the ratio of the concentrations of sulphate ion and carbonate ion is constant. Therefore, if, after equilibrium has been attained, we add SO_4'' (as Na_2SO_4), $BaCO_3$ is transformed into $BaSO_4$, until this ratio reattains its constant value; conversely the addition of CO_3'' causes the formation of $BaCO_3$ at the expense of the $BaSO_4$. In each case the amount transformed is perfectly definite; and the state of equilibrium can always be calculated if K_1, K_2, and the concentration of either SO_4'' or CO_3'' are known. If the conditions were such that the system should become saturated with respect to sodium sulphate or carbonate (or both), the equation determining the equilibrium would be somewhat more complicated; but the general result would be the same, namely, that the position of equilibrium is determined by the relative solubilities (in the particular medium) of such of the possible products of reaction (which include the original substances) as separate out as solid phases.

On this basis we can readily see why it may be that carbonic acid may displace silicic acid from a solution of a silicate at low temperatures, while at high temperatures the silicic acid may displace the carbonic acid and regenerate the silicate; and that it is unnecessary to bring in the conception of affinity or strength of acids to account for the phenomena observed. Nor is it necessary to attribute the reversal in aqueous solution of reactions such as the above to the influence of pressure, as is frequently done. It is true that pressure is required in order to retain the volatile components, the concentration of which in the vapor phase is thus determined by the pressure; but it is limited to this more or less subsidiary rôle. The predominating factor in determining the state of equilibrium in solution is temperature, which acts primarily

through its effect on the solubility relations of the substances involved in the reaction; secondarily and much less generally, through its effect on the hydrolytic dissociation of salts.

Salt hydrolysis.—It is a matter of common knowledge that the aqueous solutions of many salts are not neutral; thus for instance sodium carbonate, sulphide, and silicate are alkaline; the chlorides, nitrates, and sulphates of most polyvalent bases are acid. This behavior is attributed to a process termed salt hydrolysis, which may be represented by the reaction

$$BA + H_2O \rightleftharpoons BOH + HA$$

and occurs (to an appreciable extent) only when the acid, or the base (or both),[1] is weak.[2]

It is impossible to enter here into the theory of hydrolysis, or to derive from the law of mass action the relations which determine its extent. Suffice it to say that under constant external conditions the extent of hydrolysis is perfectly definite, and depends upon the magnitude of the dissociation constant of the weak acid[3] or the weak base;[4] or rather on the relation between this dissociation constant and that of water; so that the process of hydrolysis may be regarded as a competition for the strong base (or acid) between the weak acid (or base) and water (which may exercise either basic or acidic functions). Thus in decinormal solution at ordinary temperatures: sodium chloride is practically not hydrolyzed, sodium acetate is hydrolyzed to an extent which is just appreciable (0.01 per cent), while sodium sulphide or silicate is hydrolyzed to somewhere about 90 per cent. With rise of temperature the dissociation constant of water increases faster than that of the acids and bases; consequently the extent of hydrolysis increases markedly with rise in temperature.

[1] This case is of less practical importance, hence its consideration is omitted here.

[2] The strength of an acid (or base), in the sense in which it is used here, is measured by its extent of ionization. Thus, in decinormal solution at 25°, hydrochloric acid is ionized to about 85 per cent; acetic acid to about 1 per cent; hydrogen sulphide to about 0.1 per cent; corresponding to this the respective dissociation constants of these acids are 1 (approximately), 1.8×10^{-5} and 9×10^{-8}. The dissociation constant of water at 25° is 1.2×10^{-14}.

[3] In salts which yield an alkaline solution.

[4] In salts which yield an acid solution.

Of the hydrolysis of the silicates little is definitely known, except that the ordinary solutions of alkali silicates (water glass) are nearly completely hydrolyzed into free alkali and colloidal silica. But from this it is not quite safe to conclude that the salts corresponding to all of the silicic acids (or aluminosilicic acids,[1] if such salts exist) are also completely hydrolyzed under all conditions. For it is quite conceivable that hydrolysis of a silicate may take place without producing colloidal silica; this might occur either because the silicic acid resulting from hydrolysis of the particular silicate is not colloidal or because of the intervention of factors—temperature, or the presence of other substances in the solution—which enhance the *real* solubility of silica and thus decrease its tendency to appear in colloidal form. The extent of hydrolysis under such conditions would be that corresponding to the dissociation constant of the silicic acid, which may not be so small as is commonly supposed. For in the hydrolysis of silicates, as it has been observed, the silica becomes colloidal and is removed from true solution as fast as it forms, and hence its active mass in the solution remains exceedingly small; consequently the hydrolytic dissociation continues until practically all of the original silicate is decomposed. This therefore affords us no *certain* information as to the strength of the silicic acid, for the same phenomenon would be observed even if the silicic acid were of such strength (e.g., comparable to acetic acid) that the extent of hydrolysis is of the order of 0.1 per cent; furthermore, it is no absolute criterion of what would happen if no colloidal material were formed.

The rôle of hydrolysis is important in the kaolinization of the feldspars, and in many reactions occurring in solution in liquid water; but in all probability it is altogether subsidiary—if not entirely negligible—under magmatic conditions, in which case it is preferable to regard the silicate mixture as solvent and the water (or other gases) as solute.

Most silicates react alkaline in contact with water; but according to F. Cornu,[2] an acid reaction is given by a number of minerals,

[1] To illustrate by means of an analogous case: the salts of hydrocyanic acid (HCN) are largely hydrolyzed, whereas there is very little hydrolysis with salts of hydroferrocyanic acid ($H_4Fe(CN)_6 = 4HCN, Fe(CN)_2$).

[2] Tschermak's *Mitt.*, XXIV (1905), 417.

such as hibschite, kaolin, pyrophyllite, nontronite; all closely related to the kaolin formula $R_4Al_2Si_2O_9$. Now the reaction between complex silicates and water is not necessarily simple; for instance, the reaction may be due to hydrolysis of the first products of decomposition of the silicate. Moreover, atmospheric carbon dioxide might play a part in the reaction. In this connection it is well to observe that it is incorrect and useless to speak of the *solubility* of a mineral in water, unless the mineral dissolves as a whole; just as it is useless to speak of the solubility of a metal in an acid. We may speak of solubility only when the relations between the various components are the same in the solution as in the solid, or when it is possible to recrystallize the original silicate from the solution. Otherwise we are dealing, not with a process of solution, but with a decomposition.

DIASTROPHISM AND THE FORMATIVE PROCESSES. I[1]

INTRODUCTION

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During the century or more throughout which a gaseous origin and an early molten state of the earth were accepted tenets a full system of doctrines relative to the formative and deformative processes of the earth was elaborated. In the earlier portions of the period these were largely based on the hypothesis of a thin crust floating on a liquid substratum. Later in the period various views of partial solidity grew up and modified the older tenets or replaced them with others. In more recent times essentially complete solidity has come into wider favor and been made the basis of more radical modifications. But these views of solidity were in the main derivatives from the original postulates of a gaseous origin merging into a molten state and they retained the presumptions appropriate to such earlier history. There thus ran through the whole system of tenets a thread of philosophy that shaped it in harmony with the initial assumptions. It is true that particular tenets were not always consistent with the system into which they were introduced, but this is only an inevitable incident. The solid earth of this philosophic lineage was usually of the type that holds rigidity to be but a function of viscosity. The tenets of formation and deformation built upon it embraced a doctrine of flowage of a slow secular sort directed by the principles of liquid motion restrained by viscosity. The presumption that such slow motion would take place under any appreciable stress if given time enough was a common tenet held widely and firmly. Specific doctrines of deformation and of secular tidal effects were worked out with great labor and skill on the basis of a visco-solid and even a visco-rigid earth. The tenets thus based on a solid and even highly rigid earth rounded

[1] Largely the results of studies pursued under the joint auspices of the Carnegie Institution of Washington and the University of Chicago.

out the older systems of doctrine founded on a more mobile earth into a fairly complete working scheme of inquiry and elucidation.

There were indeed individual instances in which the view of an elastico-rigid earth was entertained and yet regarded as springing from an earlier gaseo-molten state. But while thus entertained, this conception of an elastico-rigid earth was not carried out into a working system of doctrines consistent throughout with itself. There never grew out of it a panoply of tenets on which the geologist could base working hypotheses suited to his special problems on clear lines free from confusion with the tenets that sprang from a visco-solid earth. The instructor in geologic philosophy was never able to point the embryo geologists under his training to a set of views built distinctly on the working hypothesis of an elastico-rigid earth.

But aside from this deficiency, as already remarked, a quite ample system of tenets, with alternatives and divergences, has been developed, covering the full range of conceptions from the picture of an earth with a thin shell and molten interior through various grades of partial solidity up to dominant visco-solidity of a high order of rigidity.

So familiar have most of these tenets become that they often seem to stand by themselves quite independent of the hypotheses on which they were founded. By long currency they seem to have lost much of the speculative elements that really enter into them. This is not only a source of danger in itself but is likely to stand in the way of an impartial adjudication of less familiar conceptions that are not more speculative but merely seem to be so, and which are perhaps guarded by a more frank recognition of the speculative elements.

The strong support which new evidences from cognate sciences lend to the doctrine of an elastico-rigid earth, in distinction from a visco-solid earth or any form of fluidal earth, adds emphasis to the need for a system of tenets that are strictly loyal to the elastic principle. While the principles are thus loyal, the working hypotheses must obviously recognize that, though the earth may be dominantly an elastico-rigid body, it is not exclusively so. The gaseous and liquid elements are factors of moment and co-operate in

the great processes that form the earth-habit, but in this set of views it is to be assumed that they serve as subordinate elements and merely condition the dominance of elastic solidity.

The development of a system of tenets on the elastico-rigid basis is also invited by the grave objections that have arisen from new phenomena against the gaseous cosmogony and its sequences which lie back of the older system of tenets. The planetesimal cosmogony offered to meet these difficulties is founded on orbital mechanics and parts company with gaseous mechanics at the outset. Being thus dynamically diverse from the start, it has occasion for its own set of tenets. These need elaboration to meet the whole range of phenomena involved in the major problems of geology. The task of working these out has been steadily pursued but the labor is great, and progress, if guided by prudence and circumspection, is necessarily slow.

While many of these tenets of course have no immediate concern with the physics of the body of the earth and are not necessarily of the elastico-rigid order when they do, yet the dominant tendency from the nature of the hypotheses is in that direction. The planetesimal cosmogony opens the way at least for the evolution of an elastico-solid earth in the very mode of growth it postulates, though it does not exclude the possibility of a molten earth or even the probability that molten and gaseous states may dominate planets much more massive than the earth. With a body of the mass of the earth limited in its power to control the lighter gases, the trend of probabilities favors an essentially solid earth from an early stage of growth if not from the very beginning. An orbital organization may have dominated even the earth-nucleus of the parent nebula. At any rate, the long slow growth of the main mass of the planet offers rather strong presumption of a relatively cool solid accretion attended by heterogeneities of composition and differentiations of accession and crystalline organization that were never smoothed out by liquefaction but have remained of the same type as those now presented by the earth. An elastico-solid state is thus rather a matter of direct genesis than of subsequent derivation as is the case in the alternative mode of origin.

Following this hypothesis, therefore, one comes to a mature

earth with internal qualities closely like those of the accessible parts of the present body, and the working tenets that spring from this hypothesis most naturally are those founded on crystalline structure dominated by elastico-rigid properties. The conception is free from the inheritances of a liquid state with its inevitable assortments and systematic arrangements of material on the basis of specific gravity.

The conceptions of internal temperature and of vulcanism associated with this hypothesis by its author[1] are peculiarly hospitable to the development and maintenance of a solid crystalline state of the interior. They are relatively free from the postulate of very high temperatures. No occasion for a rise to the critical temperatures of rock-substance is offered and the dilemmas these bring do not trammel the problems of the planetesimal earth of the author. It is immune against the gaseous heart. The very mechanism of its vulcanism automatically forces to the surface the expansional factors that contribute to liquefaction and the gaseous state. The elements that, if retained, would lend mobility to its mass continually seek the surface, while those that contribute to stability and solidity remain within. The normal earth-habit under this hypothesis is conducive to a stable crystalline organization. This holds to as great depths as known methods of action may be safely projected. As balanced pressure contributes to solidity, it is a hazardous assumption that places narrow limits to the downward extent of solidity and the crystalline state.

Deep differentiations of specific gravity of moderate degree are natural results of a slow planetesimal growth under the conditions imposed by the early atmosphere and hydrosphere, in addition to the inequalities of infall. The inevitable deformations and gradational processes of the growing stages are presumed to have emphasized these inequalities, in certain respects, in modes of the same sort as those that affected all later history. These inherited inequalities of specific gravity are, perhaps more than any other agency, the governing power in shaping if not actuating diastrophic movements. This is the basis on which isostasy today does whatever it is competent to do toward a final equilibrium. How such a basis for

[1] "The Bearings of Radioactivity on Geology," *Jour. Geol.*, XIX, No. 8 (1911).

action could have arisen from a primitive fluidal condition is the task of those who postulate that state.

Under the planetesimal hypothesis, the earth grew slowly into the state which it still in the main retains, dominated by working methods of the same order as those that now prevail. No radical change of working tenets between the formative and the subsequent stages is required.

As already stated, the formative stages of the earth favored the retention within the earth-body of the stable crystalline compounds and the elimination of the unstable and mobile. It may be added that the formation of these stable compounds is favored by the conditions that lead to the eliminative process. These conditions were brought to bear on any given matter added to the earth first at shallow depths under moderate temperatures and pressures, and then successively at greater and greater depths, with higher pressures and temperatures, attended by the appropriate eliminations of unstable matter. This progressive action is held to distinctly favor the more and more perfect evolution of a crystalline earth-body progressively growing freer and freer of gaseous, liquefying, viscous, and colloidal elements.

Now crystals are the very type of elastico-rigid bodies. The permanent retention of their specific forms by means of definite elastico-rigid properties is one of their supreme qualities. We are not aware that there is any evidence that a crystal of rock undergoes any plastic or viscous deformation by reason of its own gravity in any known length of time. It may undergo change of form by molecular liquefaction and regelation or recrystallization, but it seems safe to challenge the citation of cases where crystals standing out from their attachments to the walls of crevices or cavities, though athwart the pull of gravity, have shown deflection or deformation, however long they may have stood in this position. The doctrine that flow will take place under gravitative stress if only time enough is allowed seems to be without the sanction of observation in this case, and equally without the sanction of sound theory when the nature of the case is precisely considered. The familiar reasoning is no doubt good for viscous bodies and for bodies in which a quasi-viscous condition can be induced by unbalanced

internal stresses. But in elastic bodies a specific amount of stress is prerequisite. The working tenets for elastic bodies must take account of this. There is a real plasticity and a quasi-plasticity.

The planetesimal hypothesis therefore lends its weightier presumptions to the belief that the earth, or at least its outer mass to great depths, is essentially an aggregate of crystals and derives from them, in a composite form, a measure of their solid elastic properties. The working tenets of this hypothesis are thus normally as distinctly elastico-rigid as are those of the gaseous genus of cosmogonies normally of the viscous type.

It has seemed worth while, therefore, to shape some of the studies in hand so that they will contribute, if they may, to the evolution of the working conceptions appropriate to masses of crystals of earth-dimensions under earth-conditions. Such articles may equally serve the more specific purposes implied by their titles. The discussions now in mind have grown out of studies on formative and on diastrophic processes. Time has changed the order of primacy from the formative of the early ages to the deformative of the later ages, at least it so seems to the student of present problems. We therefore chose the general title "Dia trophism and the Formative Processes" as a thread by which to preserve the semblance of continuity of purpose through the series of articles that may themselves seem more or less heterogeneous. The writer of this word of introduction will not be the sole contributor.

DIASTROPHISM AND THE FORMATIVE PROCESSES. II[1]

SHELF-SEAS AND CERTAIN LIMITATIONS OF DIASTROPHISM

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It will doubtless be agreed at once by all that the general configurations of the oceanic beds are due to deformative processes. There will be a readiness also to agree that the same is true of the beds of some of the seas and minor water bodies. On this background of common opinion we may discuss sea-beds that do not owe their final form to diastrophism but to gradational processes. If all of the former class, large and small, be grouped as diastrophic basins, all of the latter class may be styled gradational basins, however incompletely the term basin represents their forms. There are of course composite and erratic forms that may be neglected here. The most familiar examples of the gradational type are the continental shelves. These are here regarded as only initial forms of the type, falling far short of serving as ideal representatives of the maturest class of sea-shelves. The waters that rest upon these sea-shelves may be known conveniently as shelf-seas.

The ideal shelf-sea is not independent in origin; it is conditioned by the diastrophic sea from which it grows; diastrophism shapes the original basin; gradation superposes certain characters and extensions upon it. These new features are of radical importance in biological and stratigraphical development.

Not only are shelf-seas conditioned at the outset by diastrophism but their histories hang on its continuous or its periodic action. If diastrophism is continuous, the gradational process constantly suffers disturbance and is ineffective; if diastrophism is periodic, gradation goes forward on given lines as long as quiescence continues attaining greater and greater degrees of maturity of type,

[1] This article is nearly identical in substance with a portion of a paper read at the Twelfth International Geological Convention, Toronto, Canada, August 16, 1913.

ceasing only when its systematic work is cut off by renewed diastrophism. If diastrophism is periodic, effective gradational results are inter-periodic products; diastrophism and systematic gradation are alternately dominant. From these general considerations, let us turn to specific features.

The distinctive characteristics of shelf-seas are these:

1. *There is a close approach to parallelism between the surfaces and the bottoms of these seas.* There is but a gentle slope between their landward sides and their seaward sides or their deepest axes. In their immature stages the typical slopes may be 1 in 1,000 or 1 in 800 or steeper; in their maturity the slopes seem often to have fallen to 1 in 2,000 or 3,000 or lower. This close approach to parallelism between surface and bottom is a feature of moment in its bearings on the nature of the deposits and the character of the life.

2. *The parallelism between sea-surface and sea-bottom is close in the further sense that the two planes lie near one another.* For reasons inherent in the gradational processes, the sea-shelf is limited in depth. Beyond a certain depth of water effective transportation of sediment fails, and the further growth of the shelf is checked except as the deep in front is filled. For the limital depth, let us assume 600 feet, 200 meters, 100 fathoms, the recognized mean depth of the outer edge of the present continental shelf. Let considerable variations from this be recognized as consistent with the type, but this figure may serve as representative. Exactness in this particular is not material to the purposes of this discussion, for the distinctions to be drawn are so broad that great latitude is permissible without invalidating the arguments built upon them. The natural criterion of the type is that depth at which the agitation of waves, tides, and currents ceases to keep in effective suspension or in rolling condition so much of the terrigenous silts as constitute the larger mass of the earthy matter derived from the land. The extremely fine material that may float long and far with little motion is negligible as it does not build up the bottom on which it falls apace with the more bulky constituents. The shelf is thus a product whose configuration is determined by its own conditions; it is a self-regulated formation; the guiding element in whose genesis is the sea-surface and the agencies that play upon it.

3. *The sea-shelf is definitely correlated with the penetration of solar rays.* This is a relation of biologic moment. As the mode of formation keeps the face of the shelf within a certain distance from the sea-surface, the waters upon it have a rather definite range of illumination. Competent opinion places the larger part of the effective photo-synthetic action within a hundred meters of the surface, while photographic effects vanish at three or four hundred meters. Organisms that depend on insolation, or that live upon those that do, may be assumed to be rarely fossilized at greater depths than these when there is no ground to suspect postmortem transportation. The shelf-sea deposits therefore embrace the sessile photo-synthetic types and their dependencies. Deeper deposits may embrace the pelagic types, but rarely the sessile and quasi-sessile forms. The shelf zone is therefore from the very nature of the case a biologic horizon of the first importance. Its faunas in consequence belong to a distinctive type. The life entrapped in the bed of the shelf-sea is demarked from that caught in the abysmal bed of the ocean.

There is, however, a narrow belt about the borders of diastrophic seas that enjoys photo-vital conditions much the same as the gradational shelves, though the slopes are normally steeper and the life-conditions somewhat more special and precarious in general. A comparison of the relative values of the gradational shelves and the diastrophic belts within the same depth-limits is a critical part of this study and will be taken up presently. It thus appears that the shelf-seas are photobathic zones of special effectiveness, and are, and no doubt always have been, the habitat of a most important type of marine faunas and floras, the class most akin to the life of the land—pre-eminently the class on which the divisions of geologic history have been based, and may best be based still more specifically, so far as these divisions are biologic.

4. It is scarcely more than a reiteration of the last statement in a special form to say that the faunas of the shelf-seas of ancient times were given distinctive aspects by the conditions of insolation, of aeration, of low pressure, and of agitated bottom, all of which were determined by the mode of origin of these seas. These sea-conditions became, therefore, critical factors in the history of

ancient life. The extent and maturity of these seas has been a decisive factor in geologic history.

5. So too it is scarcely more than reiterating the statement that preceded the last to say that the typical sediments of the shelf-seas at all geologic ages were of the types that depend on agitated waters. The sediments were assorted and spread out with notable uniformity, continuity, and exceptional horizontality over wide tracts because of the conditions of formation.

6. *The shelf-seas were spread upon the continental platforms.* Diastrophic sea-basins may be *set in* between continents (Mediterranean, Caribbean, etc.) or be *sunk within* the continental platforms, but the gradational seas lay upon terraces either built out from the upper edge of the continental platforms or cut back on the upper edge of the platforms, or else were flooded forth upon the lower parts of the platforms by the partial filling of the ocean basins with sediment. They were technically epicontinental, while the diastrophic seas were usually intercontinental or intracontinental. Of course shallow diastrophic basins may be so formed as to be in a sense epicontinental, but not in the constructive sense here applied to the sea-shelves, and of course there were composite types not belonging wholly to either class.

7. *Abandoned beds of shelf-seas were transmitted to later periods, sometimes intact, oftener mutilated, and thus became important inheritances.* Diastrophism may affect distant ocean basins, increasing their capacity and drawing off the waters from above a sea-shelf, leaving it intact. The shelf may continue to escape disturbance until the inwash from all the lands of the globe so far fills the common sea-basins as to lift the sea-surface and force the waters to return upon the abandoned sea-shelf, introducing a new period of sedimentation in close conformity to the old one. Oftener the sea-shelf participates in some degree in the deformation, however preponderant it may be in distant regions, for the earth body is a physical unit and great deformations in one quarter are likely to have a greater or less effect in other quarters. The sea-shelf inherited by the following period has usually been warped in some notable measure and the later terrane is somewhat discordant with the earlier one. And yet the gradational work of the earlier period

is an inheritance of great moment. The work of regrading in the later period is relatively light and the later sea-transgression much facilitated. Even when the deformation between the periods is strongly felt within the same continent, it is usually confined to portions of the transgressive plane only and the rest remains available for the next sea advance. For example, the Mid-Ordovician transgression formed a broad shelf covering half America; this was only partially warped on its east border by the Taconic folding, and the transgression of the Mid-Silurian was greatly facilitated by its inheritance from the Ordovician. The Ordovician had received a great inheritance from the Cambrian shelf-work. The work of all these was handed on to still later periods. This leads us to note an additional characteristic.

8. *The work of shelf-seas was cumulative.* This is true also of base-planes, the working copartners of shelf-seas, but not in an equal degree. An uncovered base-plane is constantly affected by disintegration and on any upwarp to destructive erosion against which it has no protection. The shelf-sea work is constructive and on any upwarp is defended by its own deposits. While it suffers, it has resources of resistance. In addition to this, its attitude is conservative and some notable uplift is necessary to expose all its strata to removal. It thus follows that a great sea-shelf once formed usually transmits its results to successive periods, and each of these adds its own extensions. There is thus developed a succession of sea-transgressions recorded by terrane spread upon terrane, making up a series which is continuous until one of the greater diastrophisms cuts the cumulative process short.

9. *The upper faces of the continents are largely the products of the cumulative work of the shelf-seas, though much mutilated by diastrophism and erosion.* It seems safe to say that 80 or 90 per cent of the surface areas of the continents bear some evidence of former shelf-sea work and 70 per cent or more are still mantled by the shelf products, though some notable part of this mantle has lost its original flat attitude. The relatively plane upper face of the continents is to be assigned largely to base-planing and shelf-sea work in which the latter has left the more lasting, if not the greater, product. Shelf-sea work is pre-eminently a process of terracing.

It is a natural result that the continents are pre-eminently the great terraces of the globe. The picture of the continents as essentially terraces wrought upon diastrophic embossments is no doubt the truest that can be formed, and the contest between the diastrophic forces that emboss by protrusion and the gradational forces that terrace by planation and shelf-building, the chief physical battle of geologic history.

Diastrophic limitations.—Let us now consider the degree of competency and of incompetency of diastrophism to produce shallow seas whose deposits and faunas may be comparable in any serious sense with those of the shelf-seas.

If the earth-body were a perfect spheroid of revolution completely adapted to its own conditions, and if the volume of the hydrosphere were essentially what it is today, there would be a perfect parallelism between the sea-surface and the sea-bottom of the universal ocean that would be the inevitable consequence of these conditions, but there would be no sediments of the common kinds nor any life of the more familiar fossil types, but only the pelagic and the abysmal. The picture of such a state of the earth and of such an evolution as might arise from it, if indefinitely prolonged, is as far as possible from that which geologic history really presents at any known age. The actual earth has a deformed surface of such proportions that about one-third is continental protuberance and two-thirds abysmal depression, with connecting slopes between. At present about one-sixth of the continental protuberance is covered by epicontinental seas, and this sixth adjusts the one-third-two-thirds ratio to the more familiar one-fourth-three-fourths ratio of land to water so successfully inculcated by the geographies. It is the one-third-two-thirds ratio of body-protuberance to body-depression that concerns us in deformative studies. In *these* studies the modification imposed by the sea-shelf work is an incident.

These proportions have been taken of course from the present status. If it is suggested that a quite different ratio may have prevailed in early geologic times and that the ratio in the Paleozoic era may have been so far different as to leave little value in this present ratio, it is a ready reply that no special weight is placed on this ratio

as such. It is merely convenient for use in forming a concrete conception of the work of deformation taken in its largest sense. It is my belief, however, that the ratio of protuberance to depression as defined by the sea-level has not radically changed from the beginning of the Paleozoic to the present time, but geologists entertain varying opinions on this point.

It is becoming more and more clear as study proceeds that the great deformations that determine the ocean depressions and the continental protuberances are not mere superficial incidents of the earth's development. One of the latest geodetic inquiries into the distribution of gravity finds that the outer part of the earth in the United States reaches a state of isostatic equilibrium only at a depth of seventy odd miles, even when an extreme hypothesis of the distribution of differences of specific gravity is made the basis of interpretation.[1] If a natural dying away of the differences of specific gravity from the surface downward is made the basis of interpretation, the depth is much increased and may be more than doubled. The geodetic data of India, a land of great deformations, seem to demand much greater depths than the data of America.[2] Considerations that lie in the mechanics of the case strongly support the view that the portion of the earth that is involved in the highest order of deformations is both thick and stiff.

Now in the deforming of a spheroid whose yielding parts are so deep and stiff as to take on and maintain broad inequalities like the continents and oceanic basins, certain mechanical methods are inherent and inevitably express themselves in the resulting configurations; for example, the portions that are most nearly horizontal will in the nature of the case be those at the bottoms of the sags and the tops of the swells. These portions may be nearly tangent to horizontal planes, but the dips of the intervening surfaces will naturally become increasingly greater toward points midway between the swells and sags, or at least somewhere between them. If, therefore, the sea-surface lies at such a position that one-third or

[1] John F. Hayford, "The Figure of the Earth and Isostasy from Measurements in the United States," *U.S. Coast and Geodetic Survey*, Washington, D.C., 1909.

[2] G. S. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12, Survey of India*. Calcutta, 1912.

one-fourth or some considerable fraction of the upper portion of the warped surface is above it and a still larger fraction, two-thirds or three-fourths or some such fraction, lies below it, the zone of shallow water will usually cut the warps at points where they have relatively high dips. The area between the water-surface and the shelf-limit in depth will therefore be proportionately small. For a rough illustration, if the average crests of the continental swells be taken at the modest figure of 6,000 feet above sea-level and the average bottoms of the oceanic sags at 18,000 feet below sea-level, the vertical depth of 600 feet spans only one-fortieth of the total range. The value of this fraction has yet to be reduced for the excess of slope of this portion over the mean slope to give the horizontal breadth of the belt really embraced within the shelf-depth. At the present time the extreme range of deformative heights and depths is more than twice that selected as the basis of this illustration.

An inspection of present conditions seems to show that the sea surface so cuts the normal unmodified diastrophic surfaces that an area not more than half that of the present continental shelf would lie between the contours of zero and of 600 feet depth, or perhaps 2.5 per cent of the earth's surface. This differs radically from the broad areas of shallow water that obtained at the climax of the great sea-transgressions in Paleozoic times when from 40 per cent to 50 per cent of the surface of the North American continent was covered, i.e., from 16 to 20 times as much, and more or less comparable portions of other continents were covered in a similar way and at the same time. That these transgressive seas were shallow is implied by the sediments and by the faunas alike.

Various other modes of inspection lead to results of like order. The discrepancy is so great that the elements of the estimate may be liberally changed to cover all legitimate sources of doubt without affecting the general tenor of the results.

If the borders of the continents be thought to be affected by faulting in some special degree, the incompetency of diastrophism to give these nicely adjusted shelves will be emphasized rather than mitigated, for the usual effect of faulting is an increase of the abruptness of the descent from the land to the deep sea.

These facts seem, therefore, to force the serious consideration of the

proposition that the ordinary diastrophism of the earth is not suited to give the shallow-water seas which the geologic record so abundantly presents for interpretation.

If to escape the force of this proposition one indulges the inherited habit of assuming that a flat area from the sea-bottom "might have been" lifted to just the right height or let down from the land area to just the right level for this specific shallow submergence, it is well to note that the right height is only a small fraction of the full range of height involved in deformation and that the chances of the close adjustment required are correspondingly small, and should be correspondingly infrequent as well as irregular in distribution, whereas the actual case presented by the geologic seas is a systematic repetition of this state from period to period, combined with similarity of action in different continents.

If one indulges in the familiar old idea of a slow subsidence to the sea-level and below, he takes refuge in the most plausible of all diastrophic devices for meeting the actual case. In pure theory, a downward diastrophic movement has little advantage over an upward one in meeting the demands of this case. A downward movement is, however, supplemented by gradation. It is commonly assumed in such a case that the deposits build up the sinking area as fast as it descends and thus preserve an adjustment to the sea-surface. Now if the rate of deposition and the rate of subsidence were *inherently correlated with one another* so as to be co-operative in the same phase, such an adjustment would be natural and be often repeated and so meet the requirements of the case to this extent. If, for example, the weighting due to deposition were sufficient to cause proportionate subsidence, the adjustment would be easily and naturally maintained when once made. This would happen if the earth-surface were in free isostatic adjustment to this degree of nicety and the stiffness of the crust offered no effective resistance to continuous warping. On the adjacent land, however, whence the material for the deposit is being taken, the unloading should cause a proportionate rise and the sea transgression be defeated.

If, however, general elevations and subsidences are dependent on differential stresses in the body of a very stiff elastic earth capable

of accumulating strains of high value, the case is very different, for in such case the crust movements are not immediately responsive to loading and unloading. These can induce only a slight elastic strain in the elastic body. No nice adjustment to deposit can be assumed in this case. In my judgment the phenomena of geology and related sciences support this view and are distinctly opposed to a concurrent adjustment to loading and unloading of the degree of nicety required for the assigned work.

A close adjustment in response to loading and unloading seems on first thought to be supported by views of isostasy that have recently been put forth on the basis of elaborate studies of geodetic data,[1] but this seems to me an untenable application of deductions very important in their true implications, for such a degree of pliancy seems entirely inconsistent with the maintenance of the continents even on the basis of complete vertical isostasy, as will appear from considerations offered in a subsequent discussion, for any type of isostasy that is consistent with the existence of the continents and oceanic basins, as they are, *involves great lateral unbalanced stresses*.

The protuberance of the continents and their repeated rejuvenations when worn down can be explained, it would seem, only on the supposition that the mean specific gravity of the continents is lighter than that of the sub-oceanic segments. This is the postulate of isostasy. Pendulum observations confirm it. It is common ground where diverse views meet.

Now the continents are always being denuded by the mechanical action of wind, water, and gravity on the surface, and by the solvent action of water reaching to notable depths. The protuberances are not only being cut away, but are being leached all the time. There is no real weighting of the continent as a whole under normal conditions. The only apparent weighting is due to that fraction of the sediments that lodges somewhere on it in its course to the great deeps. This fraction is gathered chiefly about the edges of the continent and the weighting there is only a fraction of the unloading of the continent as a whole. The continent as such is being constantly lightened, and if it was in previous equilibrium its constant

[1] Hayford, *loc. cit.*

tendency is to rise. If it can be supposed to have been previously lifted beyond the point of equilibrium it would first be reduced to equilibrium, after which rise would follow. The most that is to be rationally assigned to the weight of sediments on the continental borders is a downward bending of the edges while the adjacent land surface rises under denudation, involving a local tilting of the surface toward the sea. The mechanism thus pictured offers no good ground for the explanation of a great sea-transgression. That the normal tendency of the continents is to rise and has been so throughout geologic history is attested by their continued existence in spite of the constant removal of their material, as also by their periodic rejuvenation and by the continuity of the land life since it began its record. If effective subsidence had habitually co-operated with denudation the disappearance of the continents would have been inevitable. The process of subsidence is not, therefore, normal to the continents. (Subsidence is of course here used in the conventional sense, subsidence relative to the mean earth surface. The mean surface itself may of course approach the center without affecting this relation.) Local or regional subsidence occasionally takes place, but for the continents it is exceptional rather than normal. Apparent subsidence is a common phenomenon arising from the filling of the oceanic basins and the lifting of the sea-level. Local subsidence, as one of the features of warping and faulting, is of course presumed to be nearly as common as the warping itself, but it is of course connected with a complementary uplift. Subsidences of these local types are not tributary to the parallelism and wide extension of the great marine deposits nor to the life adaptations of the great transgressive seas. The consistent elucidation of these constitutes the supreme problem of the geologic seas.

There seem therefore to be very cogent reasons for abandoning the traditional view that the systematic sedimentations and the systematic evolutions of faunas of the higher order are to be assigned directly to vertical or epeirogenic movements of the earth's crust.

OVERTHRUST FAULT IN NEARLY FLAT STRATA[1]

G. SHERBURNE ROGERS

During the past summer the writer in the course of an examination of a part of the ceded lands of the Crow Indian Reservation, Montana, for the United States Geological Survey, discovered a small overthrust fault in nearly flat strata. The following brief description has been written, not only because of this peculiar occurrence of the fault, but because of the extraordinarily clear and almost diagrammatic condition of its outcrop, giving the photograph a possible value for the purposes of textbook or other illustration.

The fault is located in the N.E. $\frac{1}{4}$ S.W. $\frac{1}{4}$ sec. 3, T. 2 N., R. 35 E., P.M., Montana, a point about 10 miles east of the Bighorn River and about 15 miles south of its junction with the Yellowstone. The district is on the remote edge of the Bighorn uplift, the Bighorn Mountains lying about 70 miles away, somewhat to the west of south. About 15 miles southwest of the fault in T. 1 N., Rs. 33 and 34 E., the strata dip in a general northeasterly direction at angles ranging up to 35 degrees. This dip, however, decreases in a short distance, and within a radius of about 10 miles around the fault the rocks commonly lie at angles less than one degree, except for 500 feet immediately around it where the dips locally reach five or six degrees. About 20 miles to the north the strata dip uniformly from three to five degrees in a southerly direction so that the greater part of the area examined occupies the hollow of a broad, flat asymmetrical syncline, the fault being located nearer the southern and more steeply dipping limb. Faults are not uncommon in this area, but all of the other faults appear to be normal and none was observed within 4 miles of the small overthrust in question.

The general relations of the fault, which outcrops in the north bank of the coulee, are shown in Fig. 1. The heavy black stratum is a coal bed, the dislocation of which furnishes the key to the amount of displacement and the position of the fault zone. This

[1] Published by permission of the Director, U.S. Geological Survey.

zone may be seen in the photograph to extend to the left (westward) from near the position of the hammer. It dips 29 degrees east between the ends of the dislocated coal bed but flattens to the west.

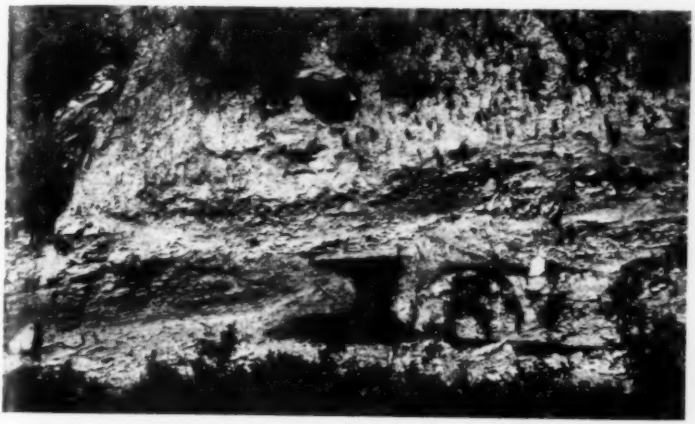


FIG. 1.—Overthrust fault cutting coal bed, sec. 3, T. 2 N., R. 35 E., P.M. Montana.

FIG. 2.—Nearer view of fault shown in Fig. 1

The peculiar shape in which the coal bed has been thrown also seems to indicate that the fault zone is not a plane but is curved near the place where it cuts the coal bed. The inclosing strata are

shale, with some sandstone, belonging to the Lance formation and overlain (see upper right-hand portion of Fig. 1) by alluvium. Fig. 2 is a nearer view of the coal bed, which is 16 inches thick, and contains a white clay parting which forms an excellent indicator of the exact character of the deformation. The total displacement is 29 inches.

The fault plane strikes north 15 degrees west. The nearest exposures along this line in either direction are about half a mile away and no trace of the fault can be found except at the locality described.

The thrust seems to have been from the northeast, i.e., toward the Bighorn Mountains. As stated above, it would seem that this fault is connected with the Bighorn uplift, but since there are very few, if any, thrust faults on the eastern slope of these mountains, and since comparatively little is known of the geology between the two localities, it is perhaps unwise to speculate on the tectonic relations of this small overthrust. A feature of greater interest is its occurrence in nearly flat strata, since overthrusting is commonly believed to be a characteristic of, and practically confined to, steeply dipping rocks. In most of the few published descriptions of apparent overthrust faults in flat-lying rocks the writers appear inclined to regard the dislocation as due in some cases to mere local squeezing, probably incident to the settling and adjustment of clay or other soft rock, or in other cases to the slight tilting of a normally faulted block.[1] In the present instance, however, the fault zone may be traced to the top of the cliff, a distance of about 35 feet across the strata, which include several thin sandstones. There seems little doubt as to its true overthrust character.

[1] The case noted by T. E. Savage in "The Geology of the Herrin Quadrangle," *Bull. Illinois State Survey*, No. 16, 1909, p. 279, may, however, be a true overthrust.

CONTRAPOSED SHORELINES[1]

CHARLES H. CLAPP
Geological Survey of Canada, Ottawa

When a shoreline which has been cut in a soft mantle covering hard rocks is, through the complete retrogression of the mantle, placed against the hard rocks, it changes radically, since it becomes dependent on the character of the hard rock surface which was covered by the soft mantle. The development of this type of shoreline is analogous to the development of superposed valleys, and in referring to the type it is desirable to use some term that shall suggest this analogy. The simplest and most evident seems to be the term contraposed,[2] meaning placed against (superposed meaning placed upon).

By the development of a contraposed shoreline, a shoreline may change during a single cycle from mature to youthful. Early in the cycle when the shoreline is cut in the soft mantle it must be simple, nearly straight, and cliffed, submature to mature. As retrogression proceeds the soft mantle is pushed back to the hard rocks and gradually, since the hard rocks are more resistant, is retrograded beyond them. At such a point in the cycle the shoreline is entirely in the hard rock. Hence it is identical to one developed by the depression of a hard rock surface, and is consequently in a youthful stage.

The accompanying block diagram illustrates three stages in the development of a contraposed shoreline. The far block indicates the conditions existing during the early part of the cycle, when the shoreline is cut in the soft mantle. The middle block indicates the conditions when the mantle is retrograded in places beyond the hard

[1] Published with the permission of the Director of the Geological Survey of Canada. Acknowledgment is due Professors W. M. Davis and D. W. Johnson who suggested that I devise a name for the type of shoreline described.

[2] As superimposed has recently and conveniently been contracted to superposed, contraposed is preferable to contraimposed.

rocks. The front block illustrates the conditions existing after the complete retrogression of the soft mantle.

Near Victoria, British Columbia, the development of contraposed shorelines may be seen in all stages, and a short description of them will be pertinent to the introduction of the term contraposed. Apparently the depression and subsequent partial recovery of the submaturely glaciated and drift-covered crystalline rock lowland of southeastern Vancouver Island initiated the present marine cycle. The initial shoreline must have been rather simple, with smooth

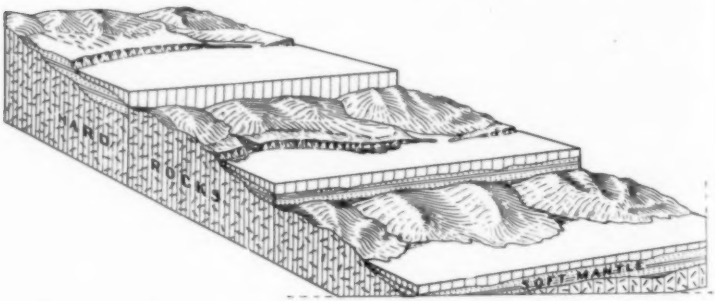


FIG. 1.—Block diagram illustrating the development of a contraposed shoreline

flowing outlines where the crystalline rocks were drift covered, but in a few places where the glaciated rock surfaces were not drift covered, it must have been characterized by many small rounded and smoothed irregularities.

During the present marine cycle the shore has been subjected to moderately strong erosion and the uplifted drift deposits have been rapidly retrograded to form sea-cliffs 200 to 250 feet high with sandpits and bars, and in places, as on the west shore of Royal Roads (see Fig. 2), a nearly straight, mature shoreline. In many instances as along the shore south of Victoria, the drift has been retrograded in places beyond the underlying crystalline rocks. These form small sub-sharp to rounded points, which project beyond the even-cliffed shoreline, the drift-cliff now occurring a few feet or yards back of high-water mark (see Fig. 3). In still other instances, as on the shore of Esquimalt peninsula (see Fig. 2), the

drift has been completely retrograded and the result is a very young, contraposed shoreline. Hardly any of the initial irregularities have been destroyed. On the contrary in the sheared zones, dikes, and interbedded softer rocks small coves and wave-chasms have been cut. The hard rocks themselves have not been beached, but since

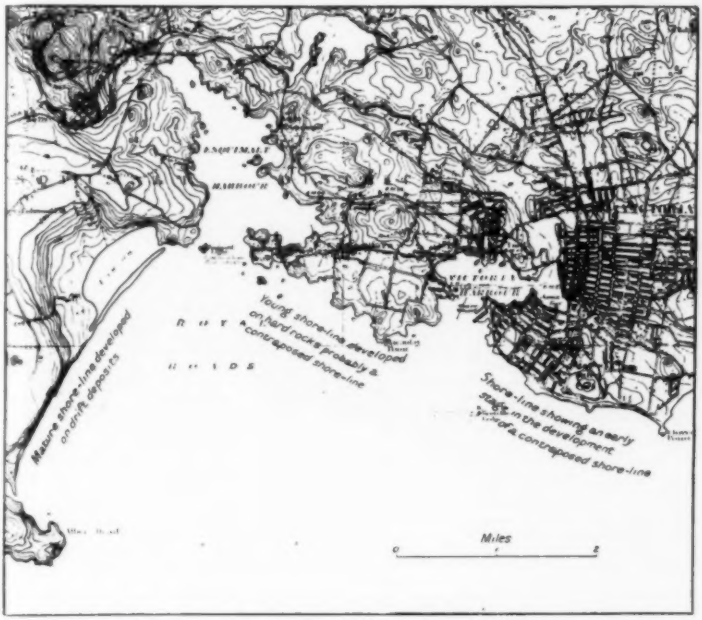

Mature shore-line developed on drift deposits
Young shore-line developed on hard rocks probably a contraposed shore-line
Shore-line showing an early stage in the development of a contraposed shore-line
Miles

FIG. 2.—Part of the Victoria topographic sheet, Geological Survey of Canada

the retrograded drift deposits frequently occur between headlands of hard rock, there are narrow beaches composed of their material in the protected places of the headlands.

It has been objected to the term contraposed, that it could not be applied on a large scale, that is, that contraposed shorelines would always be very limited in extent. This is more or less true; although one can imagine an extensive contraposed shoreline formed by the retrogression of an extensive coastal plain deposit back to the

older and presumably harder rocks on which the coastal plain deposits were laid down. There are, however, no mapped, good and clear examples of such a shoreline, although much of the Pacific shoreline of North America from Vancouver Island south may be of this character, since even where the shoreline is cut almost entirely in hard rocks, there are remnant patches of coastal plain deposits; while between the stretches of rocky shoreline are long

FIG. 3.—Contraposed shoreline, showing hard rocks overlain by retrograded soft mantle. Shore south of Victoria, British Columbia.

reaches of mature shoreline cut in extensive coastal plain deposits. The development of the Pacific Coast shoreline has, however, been complex, while the development of an ideal contraposed shoreline is simple, taking place during a single cycle, during which there is, of course, a still stand of the land. But on a relatively small scale, contraposed shorelines are so very frequent in occurrence and so strongly marked and easily recognized, that some generally accepted term for them will be a great convenience.

THE BEARING OF PROGRESSIVE INCREASE OF VISCOSITY DURING INTRUSION ON THE FORM OF LACCOLITHS

SIDNEY PAIGE[1]
United States Geological Survey

The attention of geologists has been called on several occasions to the laccolithic intrusive bodies of the northern Black Hills, South Dakota. Russell[2] has described and offered explanations for a number of the phenomena there observed. Jaggar and Howe[3] have published a detailed account of the region and performed experiments illustrating the processes which are believed to have led to the formation of laccolithic intrusive bodies; and others have commented on the work of these men, in discussing other regions where similar phenomena may be observed. The classic work of Gilbert[4] and the equally careful studies of Pirsson and Weed,[5] Cross,[6] and others have contributed to placing the theory of laccolithic intrusion on a firm basis. The type of laccolithic structure about to be described has certain peculiarities, to explain which the writer resorted to speculation and came to conclusions for which he later found partial support in the accounts of earlier writers, particularly Pirsson. In the case in point the process which is invoked as an

[1] Published with the permission of the Director of the United Stated Geological Survey.

[2] Israel C. Russell, "Igneous Intrusions in the Neighborhood of the Black Hills of Dakota," *Jour. Geol.*, IV (1896), 23–43.

[3] T. A. Jaggar, Jr., *The Laccoliths of the Black Hills;* Ernest Howe, "A Chapter on Experiments Illustrating Intrusion and Erosion," *Twenty-first Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1901), pp. 165–303.

[4] G. K. Gilbert, "Geology of the Henry Mountains," *U.S. Geographical and Geological Survey of the Rocky Mountains Region*, 1880.

[5] W. H. Weed and L. V. Pirsson, "Geology and Mineral Resources of Judith Mountains of Montana," *Eighteenth Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1898), pp. 445–614.

[6] Whitman Cross, "The Laccolitic Mountain Groups of Colorado, Utah, and Arizona," *Fourteenth Ann. Rept. U.S. Geol. Survey*, Pt. 2 (1892–93), pp. 165–258.

important factor in determining the form of certain laccoliths—increasing viscosity during intrusion—is believed to have been carried to its ultimate results. Since this phase of the discussion has not been presented before in a connected way, the writer hopes the following notes may be of interest.

Near the northwest corner of Spearfish quadrangle in the Black Hills of South Dakota, Crow Peak reaches an elevation of 5,785 ft. This peak is the crowning point of a rugged, sharply dissected, isolated mountain about 1½ miles long and a mile wide, its larger dimension lying north-northwest.

The mountain owes its presence to an intrusive mass of quartz monzonite porphyry. This porphyry outcrops as an elliptical area with its longer diameter (about a mile) trending north-northwest. Where the porphyry breaks through the overlying sedimentary rocks the strata have been bent sharply upward and steep dips (up to 90°) are found at all points on the periphery of the intrusion. These dips become much gentler a short distance from the intrusion and within a half-mile or less the beds have assumed the nearly horizontal attitude prevalent over this region.

There is strong presumptive evidence, however, that the igneous mass has a tongue-like extension northwestward beneath the sedimentary rocks, for the axis of a clearly defined anticline extends in this direction for several miles from the base of the mountain. Such an extension is not indicated to the southward.

The sedimentary rocks involved at this place rest upon a pre-Cambrian basement and are as follows: Cambrian quartzite, sandstone, and shale (Deadwood formation), almost invariably a thin shale at the top above a thin quartzite, 400 ft. ±; Ordovician limestone (Whitewood), 80 ft. ±; Carboniferous: shaly Englewood limestone at base 30 ft. ±; overlain by Pahasapa limestone, 550 ft. ±; succeeded by Minnelusa sandstone, 400 ft. ±; in all 1,460 ft. ±.

A conception of the mechanics of the intrusion must be in large part based upon speculation, for data are not at hand even to definitely establish the underground form of this igneous mass. As may be seen on the map (see Fig. 1), the northern half of the intrusion cuts as high in the sedimentary beds as the base of the

Whitewood limestone. Lowest Cambrian strata are reported by Jaggar, in a tunnel, on the north end of the mountain.[1] On most of the southern half of the porphyry, however, the intrusion reaches the Pahasapa limestone, while at the extreme southern end the Minnelusa sandstone is cut by the igneous rock. Near this latter locality a small mass of Cambrian sandstone was observed, so situ-

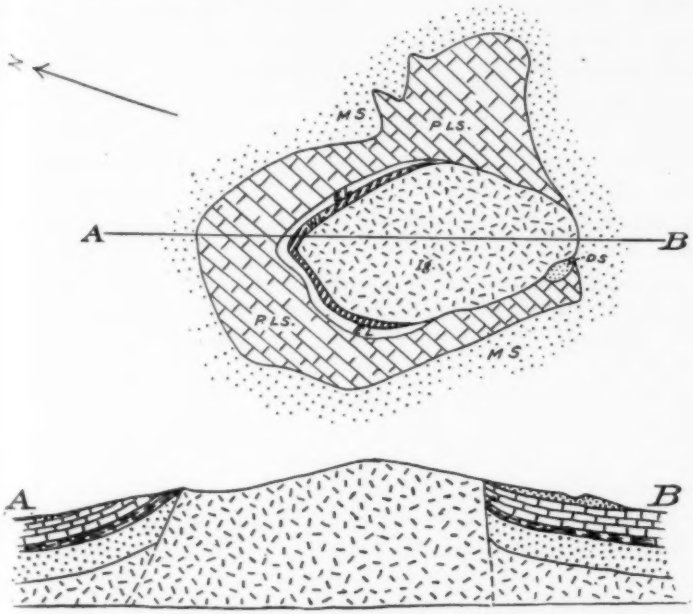


FIG. 1.—Geologic map and cross-section of Crow Peak (Paige): DS, sandstone of Deadwood formation; WL, Whitewood limestone; EL, Englewood limestone; PLS, Pahasapa limestone; MS, Minnelusa sandstone.

ated that only faulting could explain its presence. As figured by Jaggar, both in plan and in cross-section the impression is given that this mass is a symmetrical laccolith either within the Deadwood formation or between the Deadwood and the underlying schists. The cross-section especially suggests that the sedimentary

[1] T. A. Jaggar, Jr., "The Laccoliths of the Black Hills," *Twenty-first Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1901), p. 242.

strata once passed unbroken over a steep dome. In fact, Jaggar refers to this mountain as a type of steep-dome laccolith.

The facts presented above (Fig. 1) show that this is not strictly the case. The intrusive evidently cross-cuts much of the Cambrian section at the northern end of the porphyry, while at the southern end even the Whitewood, Englewood, and Pahasapa limestones are transected. The presence of a small mass of Cambrian sandstone lying against the porphyry on the one hand and the Minnelusa sandstone on the other hand adds weight to this idea that the magma violently forced its way through this portion of the overlying strata much as a punch might perforate plastic material. It is probable that such evidence of violent dislocation decidedly influenced the conclusions of Russell when he termed these masses igneous plugs. Considerations which take into account, however, the configuration of a great number of intrusive bodies in this region, and an examination of the surface structure in the region about Crow Peak leave little ground for supposing that this Crow Peak uplift is different in its broad essentials from these other laccolithic bodies, and it only remains, therefore, to discuss and offer a plausible explanation for its difference in detail, that is, the evidently violent rupture of its summit and the particular curve which the dips of the sedimentary cover would indicate that the magma possesses beneath its covering strata.

It is of interest first to call attention to a fundamental difference in the character of the curve on the upper surface or flanks of the Henry Mountains laccoliths and that on many of the Judith Mountain laccoliths, Montana. Pirsson[1] has noted this difference but does not comment upon it at length. The ideal cross-section of the laccoliths of Mount Holmes[2] (see Fig. 2) as drawn by Gilbert after a careful study of the field may be compared with a typical cross-section as drawn by Pirsson[3] (see Fig. 3) of Judith Mountain. While the cross-section of the upper surface as pictured by Gilbert is everywhere convex upward, that pictured by Pirsson is locally very straight or slightly concave upward.

[1] *Op. cit.*, p. 580.

[2] Opposite p. 28.

[3] *Op. cit.*, Plate LXXXII, section A.–A.

The writer in seeking an explanation for the condition at Crow Peak, and led by the result of one of Howe's experiments in artificial laccolith building,[1] formulated the hypothesis that the form of the upper surface of a laccolith might be materially affected by the progressive increase in viscosity of the magma during injection.

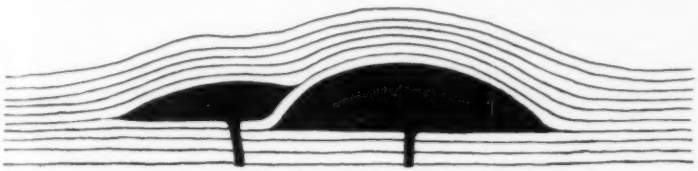


FIG. 2.—Ideal cross-section of the laccolites of Mt. Holmes (after Gilbert)

It was postulated that due to pressure from beneath, magma in fluid condition was introduced at the base of a sub-horizontal sedimentary series, and insinuated itself along the basal contact forming a thin sill or sheet of roughly circular outline. Such a sheet would exert hydrostatic pressure, which if sufficiently great to

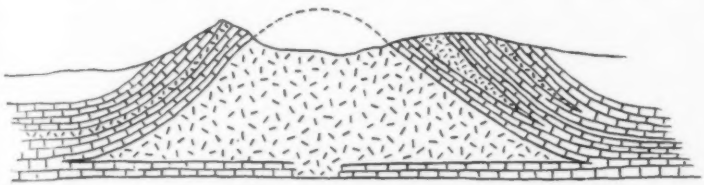


FIG. 3.—Section of laccolith in Judith Mountains (after Pirsson)

overcome the weight of the overlying strata would initiate the formation of a dome. If introduced with great rapidity such a sheet theoretically might take the form of the Shonkin Sag laccolith[2] (see Fig. 4) described by Pirsson for this form suggests that the lava, being introduced rapidly in a thin sheet, attained eventually an area over which the hydrostatic pressure was sufficiently great

[1] *Op. cit.*, experiment III.

[2] W. H. Weed and H. V. Pirsson, "Geology of the Shonkin Sag and Palisade Butte Laccoliths in the Highwood Mountains of Montana," *Am. Jour. Sci.*, 4th series, XII, 1–17.

suddenly to lift the cylindrical mass of rock above it. Pirsson reaches the conclusion that this magma was introduced rapidly, but on other grounds.[1] He says: "The occurrence of ball-like masses in the upper crust of the laccolith seems to show that the filling took place with considerable rapidity." If now it be conceived that magma was introduced more slowly or that its viscosity was greater, thereby interfering with the operation of the law of hydrostatic pressure, the factor of marginal cooling with concomitant increasing viscosity becomes a factor of importance.

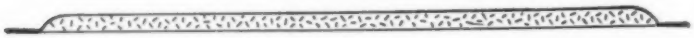


FIG. 4.—Cross-section of Shonkin Sag laccolith (after Pirsson)

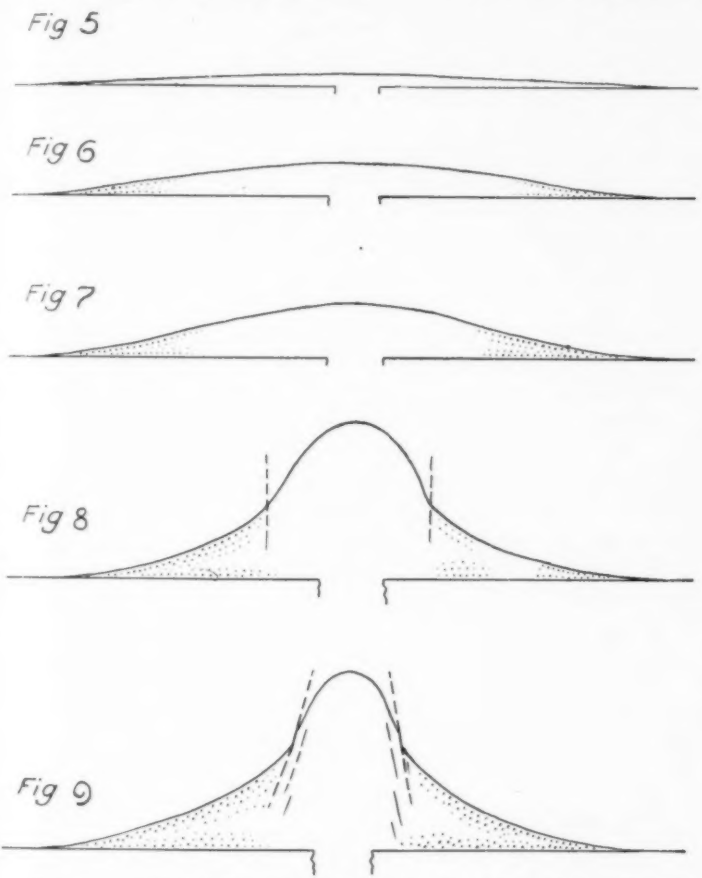
For just as much as the law of hydrostatic pressure is prevented from acting or forced to act more slowly, just so much will there be unequal distribution of upward pressure. The region of greatest pressure will be where the magma is most fluid, i.e., directly over the source of supply, while from this region outward, decreasing pressure will be exerted on the roof. The series of diagrams (Figs. 5-9) illustrate what might take place during intrusion under such conditions. The outer border congealing first, the area of perfectly transmitted pressure would be reduced, and each successive[2] application of pressure would therefore serve to accentuate the upward curve of the strata, that is, the curve on the surface of the laccolithic flanks in such a system would be more or less concave upward.

At one end of the series, then, we would have the Shonkin Sag type with a flat top; under condition of intermediate viscosity the type depicted by Gilbert (where the progressive increase of viscosity was not sufficient to form a curve concave upward, though sufficient to prevent a flat roof); and at the other extreme the type which the Judith Mountain masses approach and which Crow Peak may possess in even greater perfection.

[1] *Op. cit.*, p. 12.

[2] The process was probably continuous in its effect but successive steps are used to express more clearly the idea.

If now this system be carried to its ultimate end what will result? Obviously the dips of the sedimentary strata will approach



FIGS. 5–9.—Series of diagrams illustrating the effect of marginal cooling and increasing viscosity on the curve of a laccolithic surface.

the vertical, and if the central portion of the igneous mass is still competent to transmit pressure either by hydrostatic means or by direct thrust through a central core now become very viscous, it

is quite possible that breaks will occur and their configuration will be more or less circular—the fault surface more or less cylindrical.

It is this end which is believed to have been reached at Crow Peak. In this connection attention is again directed to the horizon against which much of the intrusion now rests, viz., soft shale of the Deadwood formation, and to the small fragment of sandstone of the Deadwood formation faulted against Minnelusa sandstone at the southern end of the intrusive mass. The shale of the Deadwood formation would form an ideal locus for such a break as is hypothesized after the beds had assumed high dips; and the block of sandstone of the Deadwood formation may well represent material dragged up along a fault plane.

Iddings says:[1]

> But when vertical displacement with faulting is one of the chief characteristics of the intrusion a distinction from normal laccolithic intrusion should be recognized. In the extreme this would result in the forcing upward of a more or less circular cone or cylinder of rocks which might be driven out at the surface of the earth, not necessarily in a coherent condition, or might be arrested at any stage of such extrusion and so might terminate in a dome of strata resembling the dome over a laccolith. By this mode of intrusion the vertical dimension of the intruded mass becomes still greater as compared with the lateral dimensions, so that its shape is more that of a plug or core.
>
> Such an intruded plug of igneous rock may be termed a bysmalith. There is then a transition from a flat intrusive sheet to a laccolith with lenticular form and from this to a bysmalith with much greater depth and considerable vertical displacement.

Jaggar in commenting on the description of Mount Holmes by Iddings, says:[2] "The sections and the text indicate that the mass described resembles the steep-sided laccoliths of the Black Hills and that it breaks across strata in the manner of a stock."

Before summing up, specific reference should be made to the work of Pirsson. He says:[3]

> It is of interest to note that the convexity of a laccolith is not a necessary function of its depth but of the viscosity of the lava in relation to the other factors; hence laccoliths of various shapes and sizes may be found in the same horizon. We have seen this, from the present work, as occurring in the Judith Mountains.

[1] J. P. Iddings, "Bysmaliths," *Jour. Geol.*, VI (1898), 705.

[2] *Op. cit.*, p. 289.

[3] *Op. cit.*, pp. 585–86.

It also seems evident that the rate of supply, or the time within which the force acts, must have a bearing in this case, and it is imaginable that the upward propulsion of the magma might be so rapid that a small laccolith could be formed where the arch of the strata was such that it was within the limits of plasticity and would tend to maintain itself after the upward force ceased, even though the magma was in an extremely liquid state.

Also, there is with a given source of supply and a given viscosity a certain limit beyond which a lava cannot form a sheet, but, if the supply of material continues, must form a laccolith. For at a certain radial distance from the supply the internal viscosity, assuming even that its ratio remains the same, will check the transmission of pressure and the onward-propelling, splitting force of the lava; but, the supply continuing, the strata must uparch and form a laccolith.

Pirsson recognized other factors in the problem besides that of viscosity, but they have not a direct bearing here. If any contribution is made at this time, it lies in the suggestion of the function of *progressive* increase of viscosity and its effect on form and in suggesting that, though varying end results may seem to be types which at first sight call for separate classification, they are in fact but stages in a process, the underlying forces of which are generically alike. To be precise: If we select Crow Peak as a type which superficially has characteristics of a volcanic plug as hypothesized by Russell (from descriptions of Newton and Winchell), we reach the conclusion that on a laccolith there was developed a form truly pluglike and that faulting is present of a sort fitting well that which circumscribes a bysmalith. And we suggest that such a cycle of phenomena may be in large measure the result of progressive increase of viscosity during the intrusion of a laccolithic mass; and further, that a series with Shonkin Sag at one end, the convex forms of the Henry Mountains in an intermediate portion, and the concave forms of the Judith Mountains at the other end, may be due largely to the same influence.

CROSS-BEDDING IN THE WHITE RIVER FORMATION OF NORTHWESTERN SOUTH DAKOTA

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Rocks of White River (Oligocene) age have been known for many years to constitute numerous isolated buttes and mesas in the northwest corner of South Dakota, but no detailed study of their character and structural relations had been made until 1911, when, during an examination of the lignite area of that country, the writer had occasion to study the relation of the younger rocks to those containing lignite beds.

Todd,[1] in 1895, recognized the White River formation in the Slim Buttes and called attention to the area in the following language:

> 3. Miocene beds, both White River and Loup Fork, with characteristic fossils, have been found overlying wide areas of the Laramie north of the Black Hills, covering quite deeply most of Harding County, with thin outliers over the north half of Butte County and south half of Ewing. In the Short Pine hills and Slim Buttes these deposits exhibit a depth of 200 to 400 feet with characteristic fossil features closely resembling those of the White River region.
>
> 4. An area of disturbance was found in the north half of Slim Buttes in northeast Harding County covering perhaps 20 to 25 square miles. This consists of sharp folds, including the Laramie and White River beds, with throws of perhaps 100 feet and dips of 25 degrees.

It is the purpose of this paper to show that the inclination of beds described above, as well as those exposed at several other localities in the Slim Buttes, is not a true dip due to a dynamic disturbance but is cross-bedding due to the peculiar manner of the accumulation of the White River formation.

White River beds, showing similar inclinations, are well exposed in at least three widely separated localities along the east side of the

[1] J. E. Todd, "Recent Geologic Work in South Dakota," *Am. Geologist*, XVI (1895), 202.

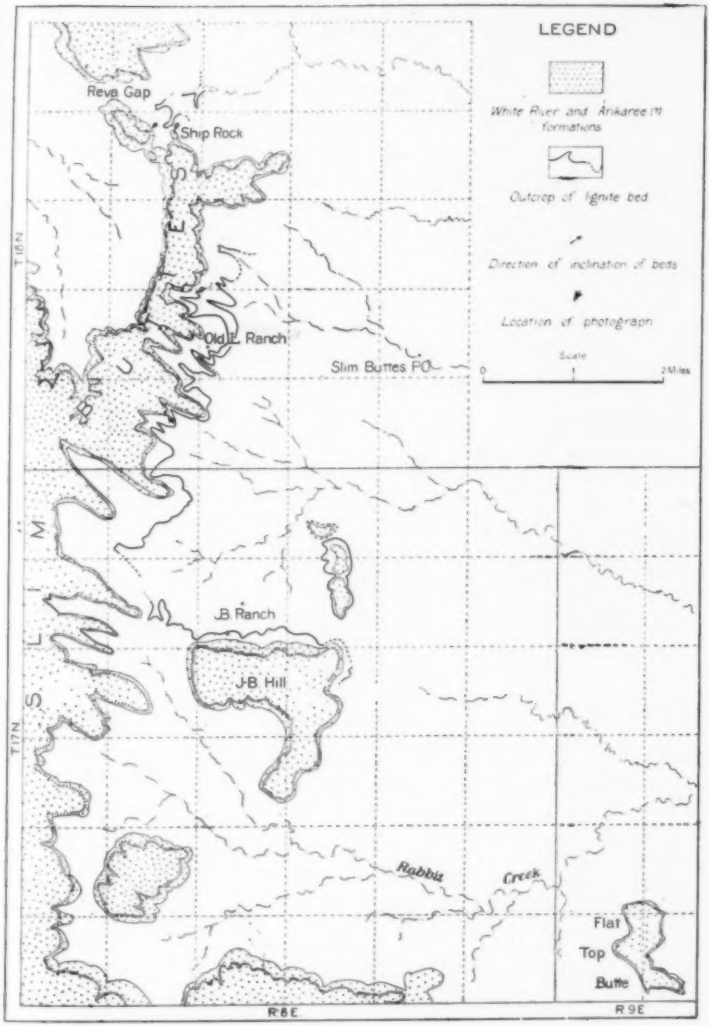

FIG. 1.—Map of part of the Slim Buttes, Harding County, South Dakota

Slim Buttes (Fig. 1): (1) in Reva Gap (Fig. 2), where the inclination is about 30° from the horizontal; (2) one-half mile south of the Old L Ranch (Fig. 4), where the inclination is about the same as in Reva Gap; (3) at the northwest angle of Flat Top Butte, where the inclination of beds is about 20°. In each case the inclined beds are overlain horizontally by a thick, characteristic sandstone, whose age is not definitely known but which has been doubtfully

FIG. 2.—Butte in Reva Gap. Height of cross-bedded portion about 75 feet

referred by Darton[1] to the Arikaree formation (Miocene). The strata beneath this sandstone include clay, marl, and sandstone, as shown in Fig. 3, in which fossils of Oligocene age are abundant. These, in turn, rest unconformably upon the lignite-bearing rocks of the region.

If the inclination of the beds in the White River formation is due to a disturbance of the strata, which occurred at the close of White River time, that inclination should also be evident in the underlying rocks of the immediate vicinity, but such is not the case, as is proven by the following facts:

[1] N. H. Darton, "Geology and Underground Waters of South Dakota," *Water Supply Paper, U.S. Geol. Survey*, No. 227 (1909), p. 21.

1. In the area between Old L Ranch and Flat Top Butte, about seven miles to the southeast, several flat-lying lignite beds are exposed, the outcrop of one (see Fig. 1) having been followed and prospected for a distance of several miles.

2. Between Reva Gap and Old L Ranch, numerous exposures show not only clay and sandstone beds of the White River formation but also the underlying lignite-bearing rocks to occupy a practically horizontal position. Ship Rock (Fig. 3), about 2,000 feet east of the point of which Fig. 1 is a photograph, exhibits White River beds

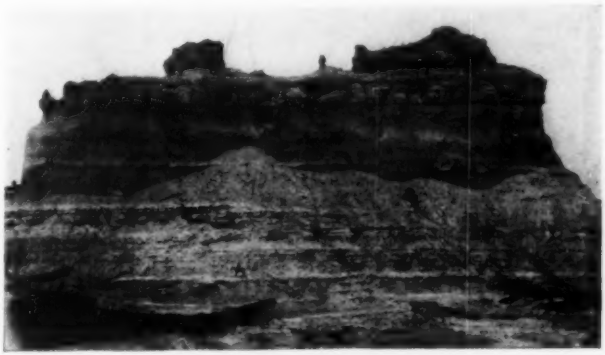

FIG. 3.—Ship Rock

in a horizontal position below the characteristic sandstone. (Photographs shown in Figs. 2 and 3 are taken looking in a southwest direction.) Hence the inclined beds cannot belong to a single anticlinal structure.

In the study of the lignite beds along the eastern margin of the Slim Buttes, still more convincing evidence was found to disprove the idea that the rocks of the region even in restricted areas were folded and faulted at the close of White River time. As is shown on the map (Fig. 1), a bed of lignite outcrops for several miles along the eastern side of the Slim Buttes in the vicinity of Old L Ranch. This bed occurs only a few feet below the White River formation and its outcrop is well exposed in sec. 32 near the point at which the photograph (Fig. 4) was taken. However,

at no point along its outcrop does the bed show a dip of more than 1°, the maximum inclination of lignite beds of the region, although it is known to outcrop in a canyon north as well as in one south of the high point in which the White River beds show apparent dips of about 30° to the southwest.

On all sides of the Slim Buttes there are large areas of slumped rocks where the attitude of the included beds seems to agree with the apparent dips exhibited in the White River beds which are known

FIG. 4.—Rocky Point, one mile south of Old L Ranch. Height of cross-bedded portion about 100 feet.

to be in place, and it is probable that these slumped rocks have been seen by former geologists and used to substantiate the apparent structure described. One large area of the White River formation, which might easily be used in this respect, is to be found at the north end of the Slim Buttes where sandstone and clay about 125 feet in total thickness, one-half mile in length, and 500 feet in width, occur as a huge landslide now occupying the bottom of a narrow valley. The beds in this block dip 10 to 15° but there is little doubt that the whole mass has moved a considerable distance horizontally, as well as at least 100 feet vertically, from its former position. However, at each of the three localities above described, the cross-bedded White River formation is exposed in the face of

high buttes and is overlain horizontally by the massive Arikaree (?) sandstone which, like the underlying strata, shows no signs of having been disturbed by either landslide or folding.

That the cross-bedding so well exhibited in the Slim Buttes is not uncommon to the White River formation is indicated by the photograph (Fig. 5), taken on Shawnee Creek about nine miles west of Lost Spring, Wyoming. In that vicinity angles of inclination of from 1–22° were observed by the writer on heavy beds of

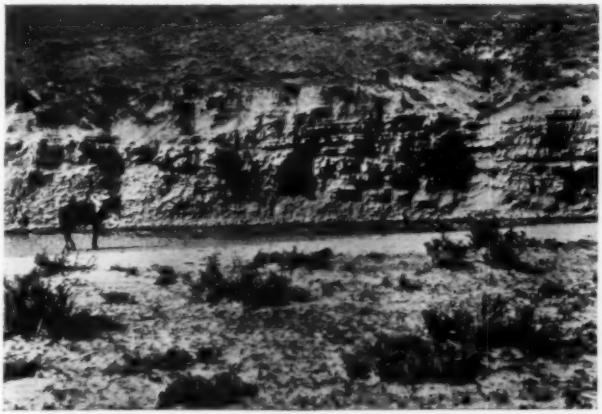

FIG. 5.—Cross-bedded sandstone in White River formation on Shawnee Creek, nine miles west of Lost Spring, Wyoming.

sandstones and conglomerate of White River age,[1] but no conclusive evidence was found suggesting deformation since the White River beds were laid down.

Until recently the rocks of the White River formation were supposed to have been deposited in a vast inland lake which covered portions of Colorado, Kansas, Wyoming, Nebraska, and the Dakotas. As the result of detailed studies, however, it is now believed by many geologists that a portion of the rocks at least were deposited along the flood-plains of shifting streams and perhaps in part by

[1] D. E. Winchester, "The Lost Spring Coal Field, Converse County, Wyo.," *Bull. U.S. Geol. Survey*, No. 471 (1912), p. 479.

wind action. The cross-bedding here described could hardly have been produced in deposits laid down in a large lake, and it requires a vivid imagination to assign it to wind action. Eolian deposits usually exhibit rather minute cross-lamination. On the other hand it is not unreasonable to assign this character of deposits to the action of shifting streams, and in that respect the author is inclined to agree with Hatcher[1] that at least part of the White River formation was accumulated as flood-plain deposits along shifting streams. Darton and others, in southern South Dakota, have been able to trace former river courses along which sandstone phases of the White River formation were deposited, but in the northwestern part of the state the formation occupies only small isolated buttes and it is impossible to trace the old drainage channels along which these remarkable examples of cross-bedding occur, so that definite data along this line cannot be obtained.

[1] J. B. Hatcher, "The Origin of the Oligocene and Miocene Deposits of the Great Plains," *Am. Philos. Soc., Proc.*, XLI (1902), 113–31.

BURIED VALLEY OF SUSQUEHANNA RIVER IN LUZERNE COUNTY, PENNSYLVANIA

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Bureau of Mines, Washington, District of Columbia

The broad river flats of the Wyoming Valley near Pittston, Wilkes-Barré, and Nanticoke, Pa., are underlain by a deposit of gravel, sand, and clay which is more than 300 feet thick in places. This material occupies a channel which was excavated in the coal measures during early Quaternary time and it is a product of river deposition. Attention was first attracted to this feature many years ago when some of the coal workings reached sand which flowed into the mines in large volume and caused great loss of life.

This buried valley was described by I. C. White in 1883 in his geological report on the region[1] and in 1885 F. A. Hill[2] published additional information regarding it. In the 1885 report[3] also C. A. Ashburner gave a description of the buried valley of Newport Creek. In 1901 William Griffith[4] published a map and view of a model showing the configuration of the floor of these buried valleys based on a compilation of all the borings and other data then available. This map shows the salient features of the valley in an admirable manner, but as numerous areas were not explored by drilling, many portions of it had to be shown hypothetically. Since that time nearly a thousand additional test holes have been sunk by the coal companies, which afford much new light on the configuration of this remarkable trough. Recently in making an examination of the region to ascertain the amount of sand available for filling coal workings I have had occasion to construct a new map, and through the kindness of the coal operators I have been able to utilize all the new data. The result is given in the map (Fig 1), which shows the

[1] Second *Geol. Survey of Pennsylvania, Report*, Vol. G 7, p. 26.

[2] Second *Geol. Survey of Pennsylvania, Report* for 1885, pp. 637–46.

[3] Pp. 627–36.

[4] *Wyoming Hist. and Geol. Soc., Proc.*, VI, 27–36, Plate 1.

salient underground relations excepting in certain relatively small areas, and also shows some minor features, although of course details can be ascertained only where the bore holes are closely placed. The configuration is represented by 50-foot contours with sea-level datum. Where the data are not complete broken lines are used, and in such places the actual contour may differ more or less from that shown. The location of the more significant borings is indicated by dots in order to show the relation of the evidence on which the representation of contour is based. To show all the bore holes would make the map too complex and for this reason also only some of the larger surface features such as river and towns are given.

Glacial features of the region.—The Wyoming Valley region lies well within the area covered by the continental ice sheet of the Glacial epoch. There is a general mantle of till interrupted only by scattered rocky ledges, and the latter show glacial rounding and striation. The striae on the mountains bear to the south but some of those on the lower lands trend to the southwestward, indicating deflection of ice movement down the valley. When the ice was thick this deflection affected only its lower part, but in the earlier and later stages the main flow was greatly influenced by the local topography. This fact was recognized by H. D. Rogers in his later publications on conditions in the region.

The till consists of the usual materials, including many rock masses from the north, and it is predominantly sandy. Some portions are a heterogeneous mixture of sand and clay of bluish tint, carrying many bowlders. It appears extensively along the lower mountain slopes and varies in thickness from 100 feet or more to a very thin veneer and locally it is represented only by scattered bowlders and blocks. In slopes east of Miners Mills and again at a point a half-mile northeast of Alden it presents morainal features with low knolls and pits. Rearranged drift abounds, mostly constituting kame terraces along the sides of the valley. Evidently these were formed when the main valley was partly filled with a lobe of the retreating ice sheet.

Configuration of the buried valley.—The principal features of the buried valley of the Susquehanna are shown on the map (Fig. 1), but there are some characteristics of special interest. It will be noted

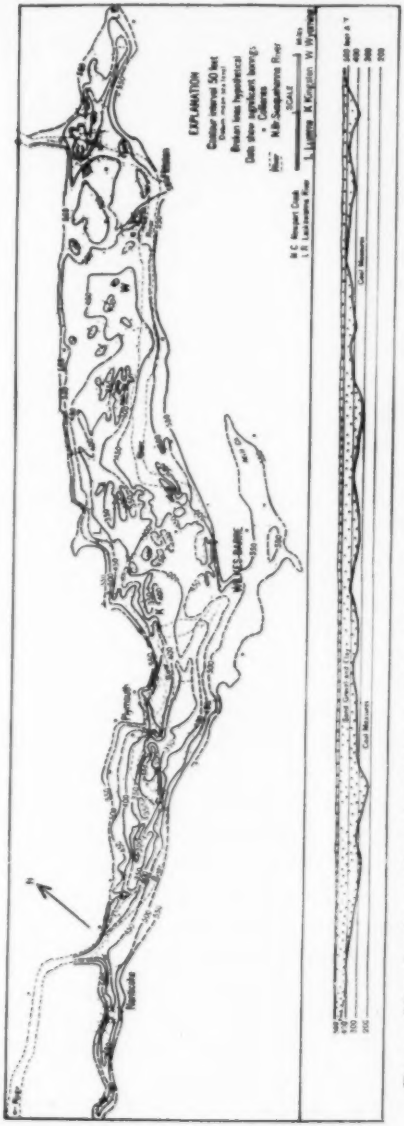

FIG. 1.—Map showing configuration of buried valley of Susquehanna River in Luzerne County, Pa., and section along its deepest portion. By N. H. Darton.

that the underground topography is very uneven and probably if all the details were brought to light much more irregularity of form would be seen. There are long basins and troughs, separated by irregular ridges and saddles, and numerous promontories project from the foot of the adjoining mountain slopes. The rocks are sandstones and shales of the coal measures and of course the excavation was effected by erosion prior to the filling of the valley. As shown on the map and section, the declivity of the underground valley is not like that of the present uniform river grade but there is a succession of irregular troughs. The deepest basin is near Plymouth from which to the southwestward there is a gradual rise of the rock floor as shown by many bore holes across the valley. Recent bore holes on the flats just east of Nanticoke show also that the rock comes to within less than 100 feet of the surface on the south side of the present stream, and as the rock outcrops on the north bank not far away from this group of holes there is no likelihood of a deep channel in the interval. Possibly it may be suggested that there is a narrow canyon cut moderately deep in the rocks here, but a feature of that sort would not be accordant with the topography of the buried channel farther upstream. As noted by previous observers, rock ledges cross the valley at no great distance downstream. The suggestion that some of the deeper basins in the valley are "potholes" is not tenable, for they are too greatly elongated to be in that category.

Materials in the old channel.—The buried channel of the Susquehanna is filled to the level of the present wide valley bottom with gravel, sand, and clay, which, as stated above, reaches a thickness of 309 feet at one place. In general the deposit varies from 100 to 200 feet thick in the greater part of the area. Sand predominates but there is a large amount of silt, or mixed clay and sand, and admixture of gravel in various forms. Some of the gravel is in beds of considerable thickness and extent, but it is generally mixed with much sand. There are many beds of clay intercalated in the deposits, one of them underlying Kingston attaining a thickness of more than 100 feet and extending for some distance up and down the valley. No definite order of strata for any wide area could be determined from the bore-hole records and apparently there is great

variation in the succession from place to place, finer sediments merging into coarser ones in a very irregular manner. There may be considerable till or glacial drift in the valley but it could not be recognized in bore-hole records. Apparently most of the materials have been deposited by the river in part by swift currents and in part in slack water under conditions not very different from present ones at time of freshet when the flats are widely flooded.

The buried channel of Newport Creek.—The deep, narrow, sand-filled basin or trough under Newport Creek valley was described and discussed by Ashburner in 1885[1] and its configuration was shown by Griffith in 1909.[2]

Later borings by the Susquehanna Coal Company have added some very important facts especially as to conditions north of shaft No. 2, where it is found that there is a rapid rise of the floor of the old valley instead of a continuous downgrade as previously supposed. Some of these data are shown in the map (Fig. 1). This valley differs from that of the Susquehanna in containing a relatively wide area of high terrace deposits rising high above the creek.

The deposit in this valley is more than 250 feet thick in places, with its base nearly 150 feet below the bed of the creek and its top constituting a high terrace which originally occupied the entire valley. The greatest width is nearly one-half mile at a point about a half-mile above Nanticoke. Near shaft No. 2 in the northern part of Nanticoke the width of deposit remaining in the valley is only 1,600 feet and the bottom of the buried valley is only 82 feet below the creek bed. The thickness of deposits also diminishes to the southwest but they extend up the valley to beyond Glen Lyon. They thicken locally near this place, for at the Catholic church the depth to bedrock is 109 feet. The material in Newport Creek valley is largely sand with scattered gravel deposits and bowlders, but some portions are so fine grained as to be classed as quicksand.

Mill Creek buried valley.—For much of its course Mill Creek flows in a wide valley that finally merges into the river terrace on which most of Wilkes-Barré is built. Now, however, the creek

[1] *Loc. cit.*

[2] *Loc cit.*

leaves this valley in the northeastern part of the city and reaches the river through a short rocky gorge. The deposits in the old creek valley are nearly 100 feet thick in places, so that their base is considerably below the level of the river. The bottom of this old valley presents considerable irregularity of contour with several deeper basins but bore holes and shafts are too widely scattered to throw much light on the details of topography.

Lackawanna buried valley.—The lower 3 miles of the valley of Lackawanna River are underlain by a buried valley which is confluent with the old valley of the Susquehanna 2 miles above Pittston. This buried valley of the Lackawanna has great declivity, for its channel deepens rapidly and its bottom is more than 150 feet below the present surface in the deep hole at its junction with the buried valley of the Susquehanna. Several basins, branching channels, and other features have been revealed by many bore holes, most of which are shown in FIG. 1.

The origin of the buried valleys.—The history of the buried valleys of Susquehanna River and the other similar features in the same region is somewhat difficult to explain satisfactorily. The channel is not an ordinary valley with continuous declivity, but, as shown by the map and section, it contains elongated rock-rimmed troughs and basins which could not have been eroded by ordinary stream action as suggested by some previous observers. The rock probably is at no great depth below the present river-bed a short distance below Nanticoke, and, even if this is not the case, ledges cross not very far southwest, so the buried valley as a whole is a basin. Deformation of an ordinary river valley since the valley was developed, as suggested by Lyman[1] and Corse,[2] is out of the question, for there are too many small depressions and ridges to be accounted for and the Quaternary deposits along the sides of the present valley show no signs of such disturbance. Probably in early Glacial time the valley was excavated by a river to a grade considerably below the present water level, but the precise depth can only be surmised. The general structure of the Wyoming Valley, a synclinal basin with a thick mass of relatively soft coal measures lying on the harder rocks,

[1] *Philadelphia Acad. Sci. Proc.*, LIV, 507–9.

[2] *Wyoming Hist. and Geol. Soc., Proc.*, VIII, 42–44.

presented a condition very favorable to the development of a feature of this kind. A stream flowing out of the mountains to the north and having sufficiently low outlet to afford declivity could naturally excavate a deep channel along this valley near the axis of the syncline. It could not, however, excavate basins with their bottom materially below its mean grade, that is, there would be no very deep holes in its course. However, when the glacier advanced southward it crossed this valley diagonally and probably picked up a large amount of loose material from its bottom. At this stage and later, subglacial streams also would have had the tendency to deepen basins in the valley bottom. It is believed then that the basins and troughs in the bottom of the old valley were excavated by glacial action largely by the removal of soft and disintegrated material by the ice as it moved across the valley. Later, when the river resumed its flow, large amounts of sand and gravel were carried down the valley and by this means the deeper parts of the old valley were filled to the present level. Apparently there was diminished declivity in this later stage or the river would have re-established the earlier gradient. The filling has continued for a long time and it is now in progress, for deposition is in excess of erosion and at times of great freshets a widespread sheet of mud is laid on the lower lands bordering the river.

The buried valleys of Mill Creek and Newport Creek with their deep holes are to be explained in the same manner as that of the river. Mill Creek has had an interesting history, for not so very long ago, geologically, it emptied into the river on the southwestern part of Wilkes-Barré. This is shown by the continuity of its old valley under the central part of the city. Later it was tapped off by a small stream cutting back through the ridge east of Prospect Colliery and it now flows to the river through a short, rocky gorge.

THE EFFECT OF LEACHING ON DRIFT PEBBLES

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University of Texas

How different rocks endure the superficial agencies of leaching and solution may be seen from the composition of pebbles in bowlder clay where this has been subjected to the solvent action of meteoric waters.

Many years ago the writer took occasion to collect fifty-eight lots of 100 pebbles each, from bowlder clay in Louisa County, in Iowa. By collecting pebbles of one size, about one-half inch, and by taking all of this size to be found on a limited space of the clay surface, unconscious selection of different kinds of rock was avoided. Thirty-seven of these samples were taken from places where the drift was in its original condition, unchanged by subsequent weathering or decay. Twenty-one samples were taken from the upper part of the bowlder clay, where it had been more or less leached and weathered.

In this region the bowlder clay is overlain by loess. The leaching of the clay sometimes extends five feet under the loess, but more often less than this. From this upper part of the till, calcareous material may be partly or entirely absent, so that there is no reaction for carbonates when acid is applied to the clay. Pebbles of limestone, which were no doubt originally present, have wholly or partly disappeared, and only less readily soluble materials remain. The leaching is most complete in the uppermost part of the till, and from here to the unaltered material below, is a zone in which the leaching is incomplete in varying degree. Limestone pebbles in this zone are either etched on the surface, or else they have suffered partial internal solution and are porous and even crumbling and are often yellow or brown from residual or infiltrated ferruginous material.

Below is a table which gives the percentages of the most important rocks noted in the study of the pebble samples collected. In

the first column are the averages of thirty-seven samples of 100 pebbles each, all from till which had not been perceptibly altered. In the second column are the averages of seven samples of 100 pebbles each, taken from somewhat leached till. The third column represents averages of seven similar samples from till somewhat more affected by leaching. The fourth column shows the average percentages for seven similar samples taken from till representing extreme conditions of leaching.

TABLE SHOWING CHANGES CAUSED BY LEACHING, IN PERCENTAGES OF DIFFERENT KINDS OF PEBBLES PRESENT IN BOWLDER CLAY

Kinds of Rocks	1	2	3	4
Flint, chert, jasper (and felsite)	11.2	27.2	45.1	59.0
Vein quartz	7.0	13.5	17.3	21.0
Sandstone and quartzite	4.7	8.0	7.0	8.0
Concretionary hematite	1.0	3.0	1.8	1.0
Granite and gneiss	7.7	11.8	7.7	5.1
Greenstone, schists (and shale)	5.5	7.9	3.7	1.9
Diabase and other volcanic rocks	10.5	15.5	8.6	2.6
Dolomitic limestone	20.10	5.3	2.4	0.2
Calcareous limestone	27.0	5.2	0.5	0.0
Decayed limestone and undetermined rocks	0.5	5.4	3.0	1.7

Under the action of the destructive agencies to which the pebbles of the drift have been exposed in this region, the ratios of the numbers of pebbles of different classes of rocks have undergone progressive changes. These changes indicate that the groups of samples represent successive stages of a general progress of solution. This progress involved a gradual removal of the most soluble rocks. The different kinds of materials are arranged in the table in the order of decreasing resistance to destruction. The end of the process in this case is the removal of practically all pebbles consisting of calcareous limestone. This results in a corresponding increase in the ratios of the numbers of the most resistant pebbles. This increase is greater or less according to the relative resistance of each class of rock.

Beginning with flint, we find that while these pebbles count only about eleven to a hundred in the till that still remains unchanged, they make, in the most thoroughly leached till, 59 per

cent. In one of the seven samples of 100 pebbles of which 59 per cent is an average, there were 70 flint pebbles. In the group of flint were counted a few pebbles of jasper and of a black felsite. Some, which here is called flint, should perhaps have been called chert, which contains some calcareous material. This is present as a mixture throughout the mass of the chert, and in the leached condition of the chert it has been dissolved away, leaving a rock which is a porous silica that readily absorbs water.

Under "vein quartz" were classified the white quartz pebbles which are derived from quartz veins in crystalline rocks, and which themselves have a crystalline structure, although the external crystalline form is hardly ever developed and only very rarely preserved in the pebbles. This form of quartz is somewhat less resistant than flint. While the percentage of flint is more than five times greater in the most leached till than in the unleached, the percentage of vein quartz is only three times as high.

Sandstone and quartzite were classified together for the reason that in the most thoroughly leached till it is often impossible correct y to distinguish the two. In leached quartzite the bond uniting the grains is sometimes weakened and the rock has in effect again become a sandstone. This may lead to the false conclusion that sandstone resists weathering better than does quartzite. Sandstone is, of course, a rock of variable qualities of resistance and strength. The varieties of sandstone and quartzite represented in this drift together are a little less enduring than vein quartz. It appears that they are only about twice as numerous as the vein quartz pebbles in the most thoroughly leached till.

Angular pieces of hematite of variable hardness are present in a small quantity in this till. Sometimes they are in part carbonate of iron. They were originally fragments of clay-iron-stone concretions, which are now mostly changed to iron oxide. Observations on compact hematite pebbles on the plains indicate that these are almost as enduring as flint, but the hematite pebbles in this till suffer somewhat more rapid destruction than sandstone and quartzite and are only about as enduring as granite and gneiss.

At first, the destruction of hematite, granite, gneiss, greenstone, schists, shale, diabase, and other igneous rocks proceeds much

more gradually than does the leaching-away of limestone. In a partially leached till, where some limestone pebbles are still left, the ratios of these rocks to the total are higher than in the unaltered till. In the classes named, gneiss, schists, shale, and volcanic rocks, other than dark diabase or diorite, form unimportant parts of the groups. Basic crystalline rocks evidently resist leaching and weathering less effectually than the acidic rocks.

Dolomitic limestone and calcareous limestone, which occur in about equal quantities in this drift, are both much more promptly removed than any of the other rocks. The ratio of such pebbles to the total is reduced to less than one fourth of its original value before the other rocks have been much affected. In the final stage the ratio of the dolomite pebbles to all others is 1:500, and the calcareous limestone has disappeared entirely. A limestone pebble is extremely rare in till, the body of which gives no reaction for carbonate of lime.

These observations show that under the conditions of weathering and leaching in the prevailing climate and drainage of this region, flint is one of the most enduring materials. It is the last thing to yield to solution and general weathering. It is relatively highly insoluble and tough. This explains why flint is a common and large ingredient in the gravel veneer found on the plains and plateaus of the West. It is always an important, and in places almost the only, ingredient in the oldest Pleistocene gravels of the South. The Uvalde formation in Texas consists of gravel consisting almost entirely of flint. About 70 per cent of the gravel taken in the Ohio at Cincinnati consists of flint and quartzite, brought largely from the residual surface material in the upper basin of this stream. Such gravels are also common in some parts of the Pennsylvanian in the central states, and these sediments are known to have been deposited during an era of extensive erosion and hence also general leaching of the land.

Reviews

Cambrian Brachiopoda. By CHARLES D. WALCOTT. Monograph of U.S. Geological Survey, No. LI, Part I, Text, pp. 1–872; Part II. Plates pp. 1–363, Plates I–CIV. Washington, 1912.

Rarely, perhaps never, has there been published a paleontological monograph so complete in every detail as this great work on the Cambrian brachiopods by Dr. Walcott. The work is not merely a monograph of the Cambrian brachiopods of North America, but of the Cambrian brachiopods of the world, and it includes also those lower Ordovician species which are close allies of, and doubtless descendants from, the Cambrian forms. The treatment of the fossil forms is both geological and biological. A large amount of geologic and geographic data, of great value to students of geology, is brought together in most convenient tabular form. Many pages are devoted to a record of every locality throughout the world from which Cambrian brachiopods have been secured, giving lists of species, not only of the brachiopods but of other fossil forms which are associated with them, and giving also the stratigraphic relations.

The zoölogical treatment of the fossil organisms is very complete. The various structural details are described with great care. Every line of investigation which gave promise of throwing light upon the relationships of these early forms was assiduously followed, and the results are clearly recorded.

The number of Cambrian species fully described and illustrated in the monograph is 477, with 59 varieties. These are distributed among 44 genera and 15 subgenera, which are grouped under 14 families belonging to the three orders Atremata, Neotremata, and Protremata. The lower Ordovician species discussed are 64 species with 3 varieties, belonging to 14 genera and 3 subgenera, and 6 families. Nearly 77 per cent of the Cambrian species are members of the two inarticulate orders Atremata and Neotremata, and the more specialized order of the articulata, the Telotremata, is not represented. In a survey of this vast array of comparatively simple types of brachiopods, a large proportion of which are of small size, sometimes even minute, many series of which are notably uniform in their general configuration, the astonishing thing is that so great an amount of generic and specific differentiation has been

so successfully determined. The lines of differentiation are shown already to have deployed in many directions in the earliest Cambrian time, and many lines became extinct during the Cambrian.

In order to show the magnitude of the contributions to our knowledge of Cambrian brachiopods during the past few years by Dr. Walcott, it is only necessary to make comparison with the number of forms recorded in earlier works. In Schuchert's *Synopsis of American Fossil Brachiopods*, published in 1897, 116 species and varieties of American Cambrian brachiopods are recorded, while in the present work 474 such forms are described, an increase of over 300 per cent. In the same work by Schuchert the following numbers of species and varieties are recorded from the remaining Paleozoic systems: Ordovician 319; Silurian 311; Devonian 663; Carboniferous 478. These numbers would in all cases be somewhat augmented were a new brachiopod census taken at the present time, but the increase would be in no manner comparable with the 300 per cent increase in our known Cambrian forms. Through the publication of this work of Dr. Walcott the records of the Cambrian brachiopod life are made more complete than for any other geologic period.

S. W.

The Physiography and Geology of the Coastal Plain Province of Virginia. By WILLIAM BULLOCK CLARK and BENJAMIN LEROY MILLER. With chapters on "The Lower Cretaceous," by EDWARD W. BERRY; and "The Economic Geology," by THOMAS LEONARD WATSON. Bull. IV, Virg. Geol. Survey. Pp. 274; pls. 19; 1 map.

A valuable and detailed contribution to the physiography and geology of the Coastal Plain. The formations are minutely described and well illustrated; tables are given containing complete lists of the fossils found together with their geographic and stratigraphic distribution.

The submerged portion of the Coastal Plain is comparatively smooth near the edge of the continental shelf, but nearer land there are numerous small hills with their long diameters roughly parallel to the shore line. The submarine covering near shore consists of fine sands mixed with broken molluscan shells, and local deposits of pebbles and blue mud; farther from shore finer deposits are found. The emerged portion of the plain slopes with gradually decreasing gradient to the shore line. Topo-

graphically it is composed of a set of five terraces designated, from the names of the formations covering them, as Lafayette, Sunderland, Wicomico, Talbot, and Recent.

The upper one, the Lafayette, has a maximum height above sea-level of about 500 feet. It is well preserved in Fairfax County, where it slopes gently to an elevation of about 200 feet and ends at the margin of the Sunderland terrace. The Sunderland terrace penetrates re-entrants into the Lafayette, and the two are, in places, separated by a well-marked scarp line. It is well developed in the central part of the province. Its eastern limit is the 100-foot contour. The Wicomico terrace borders the Sunderland and wraps around it about 20 feet below. From the contact it slopes gradually to the east and terminates at the escarpment representing the west edge of the Talbot terrace. The latter surrounds the Wicomico as a border and is separated from it by a sharp line of cliffs 10 to 20 feet high. The scarp is conspi uous just west of the Dismal Swamp. The eastern limit of the Talbot terrace is either a wave-cut cliff or the modern beach. The Recent terrace is almost wholly submerged.

The oldest series of sediments exposed on the Coastal Plain is the Lower Cretaceous. The lowest member of this series, the Potomac group, was laid down as a mixture of terrestrial, lacustrine, and fluviatile sediments, as indicated by the absence of any strictly marine fossils, and by the presence of estuarine species of shells. The flora is varied and includes equiseta, ferns, cycads, conifers, monocotyledons, and dicotyledons. The exposed thickness of the series in Virginia is about 500 feet, but a recent well at Fortress Monroe has penetrated 1,300 feet, showing an increasing thickness to the east.

The Patuxent beds rest for the most part upon the crystalline rocks of the Piedmont area, but near Doswell they lie upon the Triassic. The outcrops are conspicuous at the head of tide in the main drainage basins. The Arundel formation is not recognized in Virginia. The relation of the Patapsco beds to the Patuxent is one of decided unconformity, and the irregular erosion surface of the Patapsco is emphasized by the marine character of the overlying deposits. These resemble the Patuxent in their varied materials but are, in general, finer. The outcrops are best seen along the Potomac River near Washington.

Upper Cretaceous beds are not exposed in the region, but borings for wells have brought up fossils which have been identified as Upper Cretaceous. The material resembles the Matawan formation of Maryland and New Jersey.

The Eocene representative, which was at first thought to consist of a single formation, and was called the Pamunkey formation, has since been differentiated into two stratigraphical units known as the Pamunkey group. The lower of these, the Aquia, consists of greensands and greensand marls interbedded with occasional shell layers. Locally the beds have been subdivided into zones. The upper member, the Nanjemoy, overlies the Aquia conformably and is composed of greensands, but differs from it in having a greater argillaceous and less calcareous content. The contact is usually represented by a bed of white and pink clay. The combined thickness of the two formations is about 200 feet. The Eocene fauna is dominated by the presence of countless molluscan individuals; a total of 61 gasteropods, 60 pelecypods, and 30 protozoans are recorded. There are also five species of reptiles and eleven of fishes.

Miocene deposits have an extensive outcrop due both to their thickness and to their gentle dip. Four formations are recognized, known as the Chesapeake group. The basal member, the Calvert, rests unconformably upon the Nanjemoy, Aquia, Patuxent, and early crystalline rocks, and consists of fine-grained sands, clays, marls, and diatomaceous earths. Gypsum and glauconite are common in the clay. The width of the outcrop reaches 30 miles and is well shown in the counties of King George, Essex, Caroline, and Hanover. Above the Calvert the St. Mary's formation is present with an unconformity that represents the complete removal of the Choptank member which is present in Maryland. The deposits are similar to the Calvert except that diatomaceous earths are lacking. The upper formation, the Yorktown, is, so far as known, conformable upon the St. Mary's. It is characteristically made up of beds of finely comminuted shells apparently accumulated in shallow water. Layers of clay and sand are also present. The faunas are rich and varied and, on the whole, indicate a marine origin for the Miocene strata.

The Lafayette formation is placed tentatively in the Pliocene. It consists of unconsolidated sands and gravel, and where the deposits have been least eroded the uppermost beds are capped by loam that varies from a few inches to 10 feet in thickness. It is markedly unconformable upon all the underlying formations, and is in contact, at one place or another, with almost every older formation in the region. It is practically unfossiliferous. Its distribution is coextensive with the Lafayette terrace.

The Pleistocene formations are all surface deposits and are, in general, represented by the terraces described in the early pages of the bulletin.

The correlation of the various deposits with those of other regions is cautiously discussed. The Patuxent is correlated with the Trinity of Texas, the Lakota of the Black Hills, the Kootenai of Montana and British Columbia, parts of the Shasta group of the Pacific Coast, the Kome beds of Greenland, and possibly with the Morrison of the Rocky Mountains. The Patapsco is probably of the same age as the Fuson formation of the Black Hills, and parts of the Lower Cretaceous of the Gulf and Pacific coasts. The data are too meager to attempt correlation of Upper cretaceous deposits. The Aquia and Nanjemoy are correlated approximately with the Wilcox and Claiborne of the Gulf region.

E. A. S.

The Mount McKinley Region. By ALFRED H. BROOKS. With Descriptions of the Igneous Rocks and of the Bonnifield and Kantishna Districts by L. M. PRINDLE. Professional Paper 70, U.S.G.S. Pp. 234; Pl. XVIII; Fig. 30.

The field work for the report was done in the summer of 1902. Extreme difficulties were encountered, but in spite of them a distance of 800 miles was covered by the party of seven men in 105 days. Aside from the geological and economic discussions, the report includes a detailed narrative of the trip, a review of previous explorations and surveys, and a valuable statement of the complete equipment.

All rocks older than the Devonian are greatly metamorphosed and include undifferentiated sediments, with some igneous rocks that are thought to be Paleozoic. Rocks that may be still older than these are micaceous, graphitic, and quartz schists that occur in the northeastern part of the Alaska range and in the Yukon-Tanana region. The Ordovician rocks are blue limestones with black carbonaceous argillites, siliceous limestones, and calcareous slates, occurring along the north front of Alaska range. Some green argillites and cherts of 4,000 feet thickness are of uncertain age but are tentatively called Devonian or Silurian. The Devonian is represented by 200 feet of heavy fossiliferous limestone, 2,000 feet of chert, quartz conglomerate, sandstones, and slates, together with some volcanic rocks which may belong to the Carboniferous.

The Mesozoic group is abundantly represented by Lower, Middle, and Upper Jurassic rocks of great variety and thickness. There are remnants of igneous activity at the base and the top of the Jurassic.

The Cretaceous beds are sedimentary and less thick than the preceding ones.

The thickness of the Kenai formation ranges from 150 to 10,000 feet and embraces widely distributed outcrops of conglomerates, sandstones, shales, and coal beds. The last period of diastrophism followed Eocene deposition. Glaciation has been an important factor in the development of the present topography.

Gold and coal are the important resources; bituminous coal is of far more commercial importance than the lignites.

E. A. S.

The Geology of the Greymouth Subdivision, North Westland, New Zealand. By PERCY GATES MORGAN. Bull. 13 (New Series), Geological Survey Branch of the Department of Mines. Pp. 160; pls. 6; figs. 7; maps 8; sections 3.

This area is located along the northwest shore of North Westland and includes about 510 square miles. The oldest rocks are strongly folded argillites and graywackes known as the Greenland series. These are pre-Tertiary in age, no closer correlation being offered. Next younger than these are the coal measures, of probable Eocene age, consisting of sandstones, conglomerates, shales, and mudstones. Some valuable coal seams are also included. Four divisions are recognized: the Paparoa beds of shale and sandstone; the Brunner grits, conglomerates, and sandstones; the Island sandstone; and the Kaita mudstone. It is believed that glaciers existed in the highlands which were furnishing sediments at this time.

Miocene deposits are largely marine, and contain abundant fossils in some localities, so that the age of the rocks is well established. Pliocene exposures are limited. Pleistocene morainic and fluvio-glacial gravels show that a cold climate prevailed at that time. The gravels are everywhere auriferous.

The principal economic resources are the coal beds. The amount of coal in the ground is estimated at 600,000,000 tons, about one-fourth of which is available under present conditions. There are indications of petroleum.

E. A. S.

—Seismological Society of America, Bulletin of the. Vol. I, No. 4. [Stanford University, Cal., 1911.]

———. Vol. 2, No. 2 (June, 1912). [Stanford University, Cal., 1912.]

———. [Stanford University, Cal., September, 1912.]

—Shaw, E. W., and Munn, M. J. Coal, Oil and Gas of the Foxburg Quadrangle, Pennsylvania. [U.S. Geological Survey Bulletin 454. Washington, 1911.]

—Smith, B. The Glaciation of the Black Combe District. [Quarterly Journal Geological Society, Vol. LXVIII, 1912, pp. 402–48 and Plates XLI–XLIII.] [London.]

—Smith, G. O. Thirty-second Annual Report of the Director of the United States Geological Survey, to the Secretary of the Interior, for the Fiscal Year Ended June 30, 1911. [Washington, 1911.]

—Smith, W. D. The Mineral Resources of the Philippine Islands. [Philippine Islands Bureau of Science. Manila, 1911.]

—Snelling, W. O., and Storm, C. S. The Behavior of Nitroglycerin When Heated. [Bureau of Mines Technical Paper 12. Washington, 1912.]

—Snider, L. C. Preliminary Report on the Lead and Zinc of Oklahoma. [Oklahoma Geological Survey Bulletin 9. Norman, July, 1912.]

———. Preliminary Report on the Materials and Road Conditions of Oklahoma. [Oklahoma Geological Survey Bulletin 8. Norman, August, 1911.]

—South African Museum, Annals of the. Vol. VII. Contributions to South African Palaeontology. Part IV. [Geological Survey. Cape Town, South Africa, July 5, 1911.]

—Talbot, H. W. B. Topographical Map of Meekatharra. [Geological Survey of West Australia. Perth, 1911.]

—Tennessee, The Resources of. Vol. II, No. 2 (February, 1912), No. 3 (March), No. 5 (May), No. 6 (June), No. 8 (August), No. 9 (September). [Tennessee Geological Survey. Nashville, 1912.]

—Thaxter, Roland. New or Critical Laboulbeniales from the Argentine. [Proceedings of the American Academy of Arts and Sciences, Vol. XLVIII, No. 7, September, 1912.]

—Todd, J. E. Is the Dakota Formation Upper or Lower Cretaceous? [Transactions of the Kansas Academy of Sciences, Vol. XXIV, 1910.]

—Tóth, J. Chemische Analyse der Trinkwässer ungarus. [Herausgegeben von der dem kgl. ungar. Ackerbauministerium unterstehenden kgl. ungar. geol. Reichsaustalt. Budapest: Buchdruckerei Armin Fritz, VIII, Nap–Utca 13, 1911.]

—Udden, J. A. Geology and Mineral Resources of the Peoria Quadrangle, Illinois. [U.S. Geological Survey Bulletin 506. Washington, 1912.]

—Umpleby, J. B. Bulletin No. 5, Washington Geological Survey. Part I. Geology and Ore Deposits of the Myers Creek Mining District. Part II. Geology and Ore Deposits of the Orville–Nighthawk Mining District. [Olympia, 1911.]

—U.S. Geological Survey. Mineral Resources of the United States. 1910. Part II. Nonmetals. [Washington, 1911.]

———. Press Bulletin. [Washington, September, 1912.]

—Vadász, M. E. Die paläontologischen und geologischen Verhältnisse der älteren Schollen am linken Donannfer. [Mitteilungen aus dem Jahrbuche der kgl. ungarischen geologischen Reichsanstalt. XVIII. Band, 2. Heft. Budapest: Buchdruckerei des Franklin-Vereins, 1911.]

—Van Baren, J., in Wageningen (Holland). Roter Geschiebelehm. [Sonderabdruck aus der Zeitschrift. Internationale Mitteilungen für Bodenkunde, Band I, Heft 3–4, 1912. Verlag für Fachliteratur, G. m. b. H., Berlin W 30.]

—Veatch, A. C. Mining Laws of Australia and New Zealand. [U.S. Geological Survey Bulletin 505. Washington, 1911.]

—Vicenza, Atti della Accademia Olimpica di, Nuova Serie, Volume 11, Annate 1909 e 1910. [Vicenza: Arti Grafiche Vicentine, 1911.]

—Walcott, C. D. Cambrian Geology and Paleontology II. No. 6. Middle Cambrian Brachiopoda, Malacostraca, Trilobita, and Merostomata. [Smithsonian Miscellaneous Collections Vol. LVII. Washington, March 13, 1912.]

———. Cambrian Geology and Paleontology II. No. 7. Cambro-Ordovician Boundary in British Columbia with Description of Fossils. [Smithsonian Miscellaneous Collections, Vol. LVII. Washington, March 8, 1912.]

———. Cambrian Geology and Paleontology. II. No. 9. New York Potsdam–Hoyt Fauna. [Smithsonian Miscellaneous Collections Vol. LVII. Washington, September 14, 1912.]

———. Cambrian Geology and Paleontology. II. No. 10. Group Terms for the Lower and Upper Cambrian Series of Formations. [Smithsonian Miscellaneous Collections, Vol. LVII. Washington, September 16, 1912.]

———. Notes on Fossils from Limestones of Steeprock Lake, Ontario. [Reprint of Appendix to Memoir 28, Geological Survey, Canada. Ottawa, 1912.]

—Ward, L. Keith, B.A., B.E., and Lockhart, Jack R. The Yelta and Paramatta Mines. [Geological Survey of South Australia. Department of Mines Report No. 1. Adelaide, 1912.]

—Washington Academy of Sciences, Journal of the. Vol. I, Nos. 5, 6, 7, and 8, 1911. Vol. II, Nos. 1–20. [Baltimore, 1912.]

—WATSON, THOMAS L., AND HESS, FRANK L. Zirconiferous Sandstone near Ashland, Virginia, with a Summary of the Properties, Occurrence, and Uses of Zircon in General. [Bulletin Philosophical Society, Scientific Series, Vol. I, No. 11. University of Virginia. Charlottesville, Va., July, 1912.]

———. Zirconiferous Sandstone near Ashland, Virginia. U.S. Geological Survey Bulletin 530-P. Advance chapter from Contributions to Economical Geology, 1911, Part 1. Washington, 1912.]

—WEAVER, C. E. Geology and Ore Deposits of the Blewett Mining District. [Washington Geological Survey Bulletin 6. Olympia, 1911.]

———. Geology and Ore Deposits of the Index Mining District. [Washington Geological Survey Bulletin 7. Olympia, 1912.]

———. A Preliminary Report on the Tertiary Paleontology of Western Washington. [Washington Geological Survey Bulletin 15. Olympia, 1912.]

—WEGENER, DR. ALFRED. Die Entstehung der Kontinente. [Abdruck aus Dr. A. Petermanns Geographischen Mitteilung 1912, Aprilheft.]

—WEINSCHENK, E. (ROBERT W. CLARK, translator.) Petrographic Methods. The Authorized English Translation of Part I, Anleitung zum Gebranch des Polarisationsmikoskops (Third revised edition) and Part II, Die Gesteinsbildenden Mineralien (Second revised edition). [New York: McGraw-Hill Book Co., 239 W. 39th St., 1912.]

—Western Australia Geological Survey. Annual Progress Report of the Geological Survey for the Year 1910. [Perth, 1911.]

—West Virginia Geological Survey. Detailed County Report on Doddridge and Harrison Counties. [Morgantown, 1912.]

—WIELAND, G. F. A Study of Some American Fossil Cycads. Part V. Further Notes on Seed Structures. [From the American Journal of Science, Vol. XXXII, August, 1911.]

—WILLISTON, S. W. A New Family of Reptiles from the Permian of New Mexico. [From the American Journal of Science, Vol. XXXI, May, 1911.]

—WILSON, HERBERT M., AND FAY, ALBERT H. First National Mine-Safety Demonstration, Pittsburgh, Pa., October 30 and 31, 1911. With a Chapter on the Explosion at the Experimental Mine, by GEORGE S. RICE. [Bureau of Mines. Washington, 1912.]

—WOOD, B. D. Gazetteer of Surface Waters of California. Part I. Sacramento River Basin. [U.S. Geological Survey Water Supply Paper 295. Washington, 1912.]

—WOODRUFF, E. G., AND WINCHESTER, D. E. Coal Fields of the Wind River Region, Fremont and Natrona Counties, Wyoming. [U.S. Geological Survey Bulletin 471-G. Washington, 1912.]

—WOODWARD, H. B. History of Geology. [New York and London: Putnam, 1911.]

—WOOSTER, L. C. An Esker at Mason, Michigan. [Geological Papers Kansas Academy of Science.]

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